Preprints.org

Article

Not peer-reviewed version

Dense Cold Quark-Gluon Matter Clusters and their Studies at the NICA Collider

Vladimir Vechernin * , Svetlana Belokurova , Semyon Yurchenko

Posted Date: 6 December 2023

doi: 10.20944/preprints202312.0300.v1

Keywords: strong interaction; high energy; dense cold nuclear matter; quark-gluon clusters; multinucleon fluctons; cumulative particle production; central rapidities; large transverse momentum; NICA collider

Preprints.org is a free multidiscipline platform providing preprint service that is dedicated to making early versions of research outputs permanently available and citable. Preprints posted at Preprints.org appear in Web of Science, Crossref, Google Scholar, Scilit, Europe PMC.

Copyright: This is an open access article distributed under the Creative Commons Attribution License which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

Disclaimer/Publisher's Note: The statements, opinions, and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions, or products referred to in the content.

Article

Dense Cold Quark-Gluon Matter Clusters and Their Studies at the NICA Collider

Vladimir Vechernin *, Svetlana Belokurova and Semen Yurchenko *

Saint-Petersburg State University, 7-9 Universitetskaya emb., 199034 St.Petersburg, Russia
* v.vechernin@spbu.ru

Abstract: The production of particles outside the region of nucleon-nucleon kinematics due to interactions involving dense cold clusters of quark-gluon matter in nuclei is calculated. The possibility of observing this process in the region of central rapidities and large transverse momenta in heavy ion collisions at low energies with MPD detector at the NICA collider has been demonstrated.

Keywords: strong interaction; high energy; dense cold nuclear matter; quark-gluon clusters; multinucleon fluctons; cumulative particle production; central rapidities; large transverse momentum; NICA collider

PACS: 12.39.Mk; 13.60.Hb; 21.60.Gx

1. Introduction

Long ago, in experiments [1,2] on the interaction of high-energy protons with nuclei, an unexpectedly large yield of particles into the rear hemisphere, in a region kinematically forbidden for nucleon-nucleon interaction, was discovered. This served as the basis for putting forward the hypothesis [3] about the presence of nuclear density fluctuations in nuclei, called "fluctons". It was assumed that in a target nucleus periodically two or even more nucleons can approach each other at a short distance, forming a cluster of several nucleons. In this case, the interaction of an incident proton with such a multinucleon cluster (flucton) made it possible to explain the observed particle production in the backward direction - outside the region permitted by nucleon-nucleon kinematics. Later this area of momenta was called cumulative.

Over time, when the first beams of relativistic nuclei were obtained, it became possible to study cumulative production in the region of projectile nucleus fragmentation [4,5]. In this case, it corresponds to the production of particles with a longitudinal momentum greater than that per nucleon of the incident nucleus, what explains the name "cumulative production". In both cases, in the regions of fragmentation of the target nucleus and the projectile nucleus, experimental studies of this phenomenon are limited to the region of rather small transverse momenta (less than 2 GeV) [6–10].

It was suggested a variety of models to describe the process of the formation of particles in the cumulative region. They can be conditionally divided into two large groups. The first group [11–21] assumes the presence of fluctons already in the initial state of the nucleus, and the second group of models [22–25] suggests that the dense nuclear matter clusters are formed later, in the process of a nuclear collision.

Currently, the construction of the NICA collider at JINR in Dubna [26–28], designed for relatively low energies of colliding nuclei compared to the LHC and RHIC colliders and high luminosity, opens up the possibility of studying the production of particles in a new cumulative region of central rapidities and large transverse momenta. These investigations are of great interest, since from the modern point of view, multinucleon fluctons in nuclei are clumps of dense cold baryon-enriched quark-gluon matter. Studies of the clusters of dense cold quark-gluon matter intrinsic to the nuclei are also possible (see [29]) in future experiments at FAIR (Darmstadt).

© 2023 by the author(s). Distributed under a Creative Commons CC BY license.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

In the present paper, we study the possibility of observing the particle production in the new cumulative region of central rapidities and large transverse momenta in Au-Au collision using MPD installation of the NICA complex. We estimate the yield of pions and protons in this new cumulative region due to the process of interaction of a nucleon of one nucleus with a flucton of another. To describe the dependence of cumulative particles on transverse momentum, we use a microscopic (at the quark level) approach developed earlier [16–21] for description of the cumulative particle production in the fragmentation region of one of the colliding nuclei.

2. Features of cumulative production in the nucleus fragmentation region

Most of the experimental data on cumulative production were obtained in the rest frame of a fragmenting nucleus. In this case, when incident protons are scattered on a fixed target nucleus, cumulative particles are emitted into the rear hemisphere, which is convenient for the experimental study of this process.

For the inclusive cross section for particle production in the cumulative region in pA collisions:

$$\mathrm{p} + \mathrm{A} \to \mathrm{c} + \mathrm{X}$$

the so-called nuclear scaling was experimentally established:

$$\frac{k_0\, d^3\sigma}{A\, d^3\mathbf{k}} = f(x, k_\perp)\,. \tag{1}$$

As a scaling variable x, it was proposed to use the so-called cumulative number x, defined as the minimum target mass (measured in nucleon masses) that allows the production of a cumulative particle c with a given momentum k. This variable is suitable because for an integer $x = 1, 2, 3, ...$ it determines the kinematic boundaries for the production of a particle c with momentum k when an incident proton collides with a flucton consisting of x nucleons (see Figures 1 and 2).

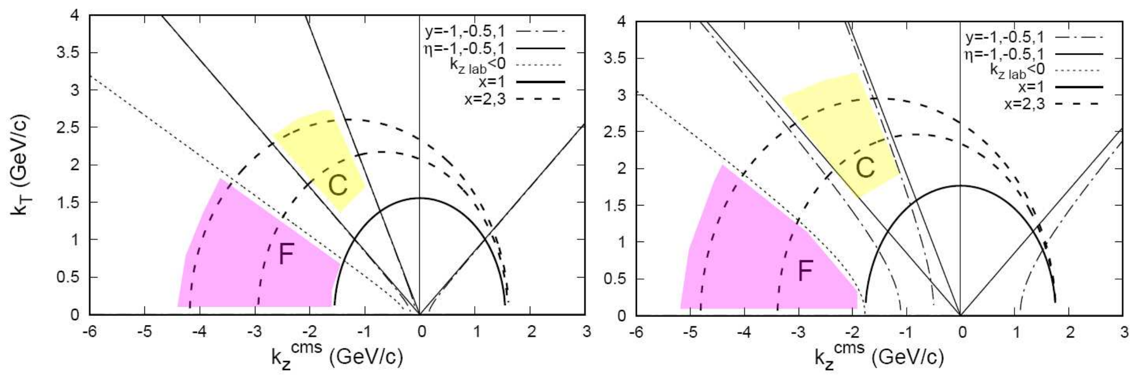

Figure 1. Kinematic boundaries for the production of pions (left panel) and protons (right panel) in the collision of a proton with a cluster consisting of x nucleons (thick dashed curve) at the initial energy $\sqrt{s_{NN}}$=4 GeV in the center-of-mass system of NN collision. The thick solid curve ($x = 1$) is the boundary of the cumulative region (production outside the NN kinematics). The dash-dotted curves and thin solid thin lines present the rapidity ($-1 < y < 1$) and pseudorapidity ($-1 < \eta < 1$) acceptance of the NICA MPD. The dotted curve is the boundary of the region F, which corresponds to the production in the rear hemisphere in the rest frame of a fragmenting nucleus ($k_z^{lab} < 0$).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

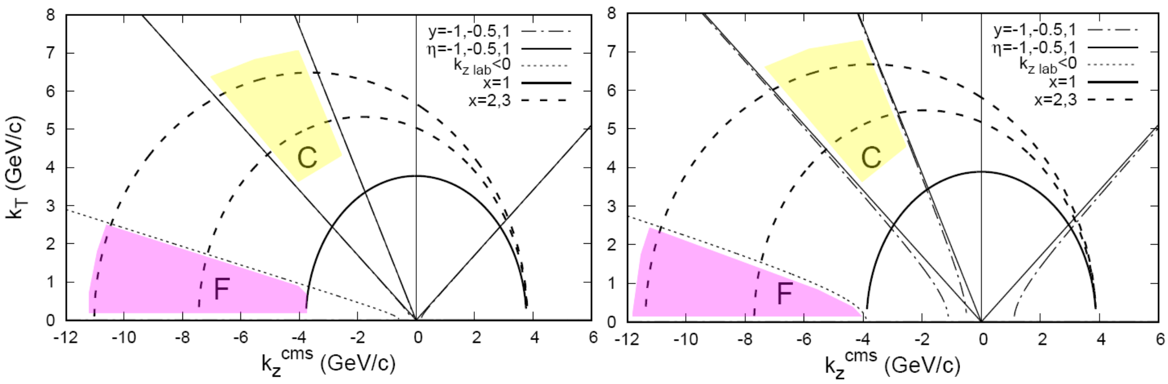

Figure 2. The same as in Figure 1, but for the initial energy $\sqrt{s_{NN}}$=8 GeV.

The variable x is also relativistically invariant and can be calculated in an arbitrary frame of reference from the equation:

$$(k, p_1) + x(k, p_2) = \bar{s}(x)/2\,. \tag{2}$$

Here p_1 is the 4-momentum of the incident proton and p_2 is the 4-momentum per nucleon in nucleus A. The $\bar{s}(x)$ is equal to

$$\bar{s}_\pi(x) = x(s - 4m^2) + \mu^2 \tag{3}$$

for production of pions and

$$\bar{s}_p(x) = x(s - 2m^2) + 2m^2 \tag{4}$$

for production of protons. Here μ is the mass of the produced particle c, m is the nucleon mass and $s = (p_1 + p_2)^2 \equiv s_{NN}$ (for more details see [34]).

For pA interaction at relativistic energies, as follows from the data (see, for example, the analysis in the articles [6,8–10]), the function $f(x, k_\perp)$ in (1) does not depend either on the initial energy ($\sqrt{s} = \sqrt{s_{NN}}$) or on the atomic number of the nucleus A (at least , for heavy nuclei). It can be presented in the following form:

$$f(x, k_\perp) = C_0\, e^{-x/x_0}\, \phi(x, k_\perp)\,, \tag{5}$$

where

$$\phi(x, k_\perp) \equiv f(x, k_\perp)/f(x, 0)\,, \qquad \phi(x, 0) = 1\,. \tag{6}$$

The value of the parameter x_0 in (5) is 0.139 for pions and 0.135 for protons, and the exponential dependence is well satisfied at $x > 1.2$ for pions and $x > 1.6$ for protons [10]. Please note that for the production of pions and protons $C_{0\pi}$=4.0·10^2 and $C_{0\mathrm{p}}$=2.64·10^6 mb/Gev^2, so, in the region of nuclear fragmentation (region F in Figures 1 and 2) the yield of cumulative protons is almost 10^4 times higher compared to pions.

As for the dependence of the yields of cumulative particles on the transverse momentum, in the works [9,10], when analyzing experimental data, it was parameterized by the Gaussian dependence:

$$\phi(x, k_\perp) = e^{-k_\perp^2/\langle k_\perp^2\rangle}\,, \tag{7}$$

and the parameter $\langle k_\perp^2\rangle$ increases with the cumulative number x and depends on the sort of the particle. These dependencies can be parameterized for pion and proton production as follows [32,34]:

$$\langle k_\perp^2\rangle_\pi(x) = 0.3 + 0.8(x - 1.2)\,, \qquad \langle k_\perp^2\rangle_\mathrm{p}(x) = 0.19 + 0.42(x - 1.6)\,, \tag{8}$$

where the square of the transverse momentum is measured in GeV^2/c^2.

This Gaussian approximation (7), used in [9,10], does not seem quite realistic to us, especially in the light of extrapolation of this dependence to the region of sufficiently large transverse momenta (region C in the Figures 1 and 2). Therefore, in the works [32,34] we proposed an alternative parameterization

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

of the dependence of the data [9,10] on the transverse momentum by a simple exponent, which usually gives a more adequate description of the data for large transverse momenta:

$$\phi(x,k_\perp) = e^{-2k_\perp/\bar{k}_\perp}\,, \qquad (9)$$

where

$$\bar{k}^2_{\perp\pi}(x) = 0.6 + 1.4(x-1.2)\,, \qquad \bar{k}^2_{\perp p}(x) = 0.14 + 0.32(x-1.6)\,. \qquad (10)$$

Unfortunately, as shown in [32,34], although both approximations provide an adequate description of the experimental data [9,10] in the nucleus fragmentation region (region F in the Figures 1 and 2) they give very different results, especially at higher initial energy ($\sqrt{s_{NN}}$=8 GeV), when we use them to calculate particle yields in the new cumulative region of central rapidities and large transverse momenta (region C in the Figures 1 and 2) available for study at the NICA MPD. In these figures we depictured the pseudorapidity acceptance ($-1 < \eta < 1$) of the MPD detector in the NN collision center of mass frame. The region F corresponds to the production in the rear hemisphere in the rest frame of a fragmenting nucleus ($k_z^{lab} < 0$).

Comparing Figures 1 and 2, we also see that in the new cumulative region the transverse momenta of particles increase with the initial energy. This explains why the study of particle production in this region are absolutely impossible at the LHC and RHIC energies.

3. Theoretical description of the dependence on transverse momentum in the cumulative region

In the present paper, to eliminate the uncertainty described at the end of the previous section and to estimate the yield of pions and protons with large transverse momenta in the new cumulative region of mid-rapidities at the NICA energies, we use the quark-parton model of the cumulative particle production from a flucton, developed earlier [16–21].

As shown in this model, the formation of cumulative pions and protons is dominated by two different mechanisms. In the case of pion production, the fragmentation of one flucton quark into a pion predominates [16–18] (see left panel in Figure 3), whereas in the case of proton production, the mechanism of coherent coalescence (recombination) of three flucton quarks into a proton is dominant [19–21] (right panel in Figure 3).

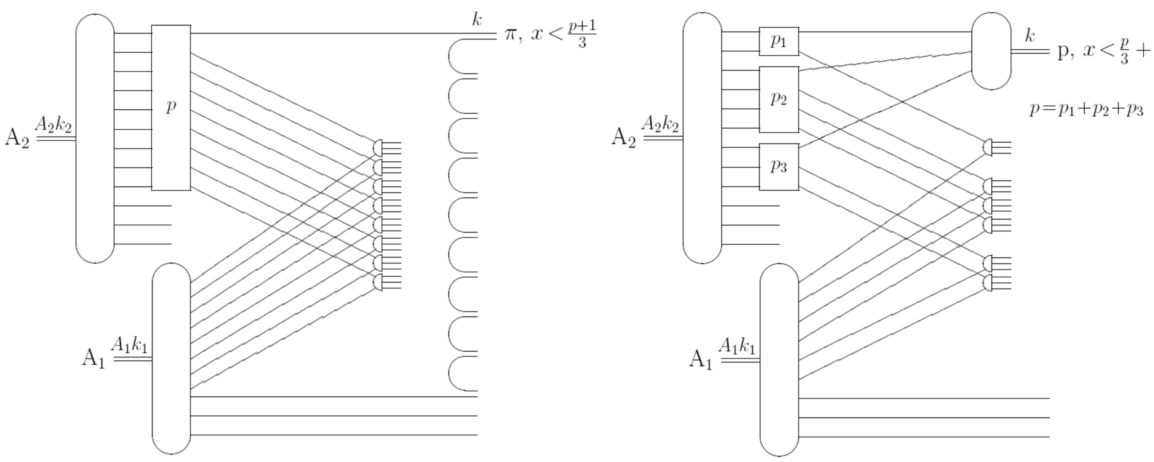

Figure 3. Formation of cumulative pions due to the fragmentation of a single flucton quark into a pion [16–18] (left panel) and formation of cumulative protons due to the coherent coalescence (recombination) of three flucton quarks into a proton [19–21] (right panel).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

As shown in [21] in the framework of this approach the dependence on transverse momentum for the production of cumulative pions is given by the expression:

$$\phi(x, k_\perp) = \Phi_p\left(\frac{k_\perp}{m_q}\right) / \Phi_p(0) \,, \tag{11}$$

where $p = [3x]$ is the number of donor quarks transferring their momentum to the active quark forming a cumulative pion ([...] denotes the integer part) and

$$\Phi_p(t) = 2\pi \int_0^\infty dz\, z\, J_0(tz)[zK_1(z)]^p \,. \tag{12}$$

Here $J_0(z)$ is the Bessel function, and $K_1(z)$ is the modified Bessel function (McDonald function). Note that for $p = 1$ the integral (12) is calculated explicitly:

$$\Phi_1(t) = \frac{4\pi}{(t^2+1)^2} \tag{13}$$

The dependence on transverse momentum for the production of cumulative protons is given by the expression:

$$\phi(x, k_\perp) = \Phi_{p_1}\left(\frac{k_\perp}{3m_q}\right) \Phi_{p_2}\left(\frac{k_\perp}{3m_q}\right) \Phi_{p_3}\left(\frac{k_\perp}{3m_q}\right) / \{\Phi_{p_1}(0)\Phi_{p_2}(0)\Phi_{p_3}(0)\} \,, \tag{14}$$

where for the considered interval of x for protons ($1.6 < x < 4$):

$$p_1 = 1 + \vartheta(x - 8/3) + \vartheta(x - 11/3) \,, \tag{15}$$

$$p_2 = 1 + \vartheta(x - 7/3) + \vartheta(x - 10/3) \,, \tag{16}$$

$$p_3 = 1 + \vartheta(x - 2) + \vartheta(x - 3) \,. \tag{17}$$

where $\vartheta(x)$ is a step function. The total number of donor quarks transferring their momentum to three active quarks forming a cumulative proton is equal to $p = p_1 + p_2 + p_3$.

Note that m_q, which is the constituent quark mass, is the only parameter in these formulas (see (11) and (14)). With a natural value of this parameter m_q= 310 MeV, we obtain a simultaneous description of the dependence of the production of cumulative pions and protons on the transverse momentum (see Figure 4).

Really in Figure 4 we see that with the natural value of a single parameter m_q this approach correctly describes the broadening of transverse momentum distributions with increasing cumulative number, which is observed for both pion and proton yields. Moreover, at the same time, it gives correct wider transverse momentum distributions for pions compared to protons for the same value of the cumulative variable. In this approach, it arises due to different mechanisms of the formation of particles with momenta outside the pp-kinematics - fragmentation of one flucton quark for a pion (left panel in Figure 3) and coherent coalescence (recombination) of three flucton-quarks for a proton (right panel in Figure 3).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

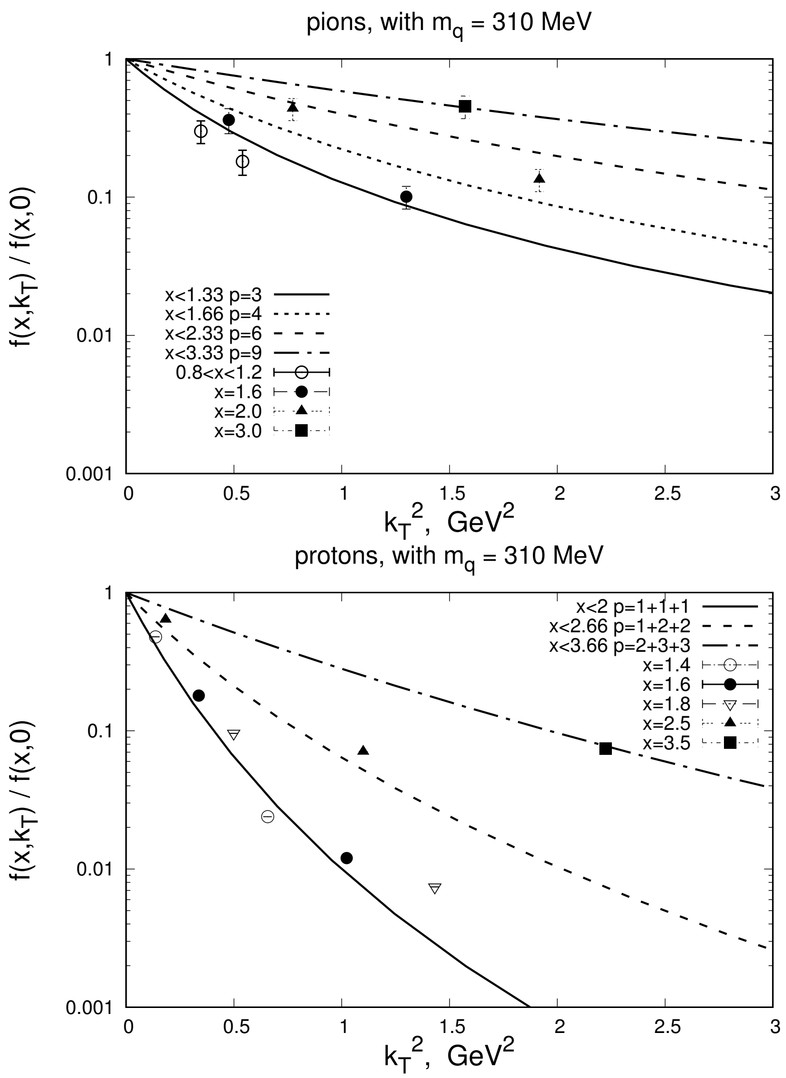

Figure 4. Dependence of the production of cumulative pions (upper panel) and protons (lower panel) on the transverse momentum $\phi(x, k_\perp) \equiv f(x, k_\perp)/f(x, 0)$ (12) , calculated by formulas (11) and (14) with the value of the only parameter m_q - the mass of the constituent quark - equal to 310 MeV. For a given value of the cumulative variable x, the number of donor quarks p is calculated as $p = [3x]$ for pion production and as $p = p_1 + p_2 + p_3$ (15) for proton production (see text for details). The corresponding experimental points are taken from the article [9,10].

4. Yield of cumulative particles at mid-rapidities in pA colllisions

In this section, we estimate the yield of cumulative pions and protons with high transverse momentum at central rapidities in pA collisions, using the theoretical description of the dependence of cumulative production on transverse momentum obtained in the previous section. The idea is to use the description of the inclusive cross section of the cumulative particle production $f(x, k_\perp)$ (1) obtained in the nucleus fragmentation region (region F in Figures 1 and 2), for to estimate the particle yields in the new cumulative region of central rapidities (region C in Figures 1 and 2), available for study at the NICA collider.

For region C (see Figures 1 and 2), the rapidity interval $-1 < y < -0.5$ is selected. We mean that in the center of mass frame the incident proton moves along the z axis, and the fragmenting nucleus moves in the opposite direction. We also exclude the region near zero rapidity, since the theoretical approach [16–21] (Figure 3), used in the previous section to describe the transverse momentum dependence of cumulative production, is not valid at small k_z^{cms} values.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

Comparing the Figures 1 and 2, we expect that the results obtained for the initial energy $\sqrt{s_{NN}}$=4 GeV will be more reliable than for $\sqrt{s_{NN}}$=8 GeV, since in the latter case it is necessary to continue the cross section $f(x,k_\perp)$ to significantly higher values of transverse momenta.

Taking into account the definition of $f(x,k_\perp)$ (1) the multiplicity of particles in acceptance Ω in pA collision is determined by the expression:

$$\langle n\rangle^{\Omega}_{\rm pA}\cdot\sigma^{tot}_{\rm pA} = A\int_{\Omega}\frac{d^3\mathbf{k}}{k_0}\,f(x,k_\perp) \tag{18}$$

Using the relativistic invariance of $f(x,k_\perp)$ we can write (18) in the center-of-mass system of NN collision and move from k^*_z to rapidity y

$$\langle n\rangle^{\Omega}_{\rm pA}\cdot\sigma^{tot}_{\rm pA} = A\int_{\Omega}\frac{dk^*_z}{k^*_0}\,d^2\mathbf{k}_\perp\,f(x,k_\perp) = 2\pi\,A\int_{\Omega}dy\,dk_\perp\,k_\perp\,f(\,x(y,k_\perp),\,k_\perp)\,, \tag{19}$$

where

$$y \equiv \frac{1}{2}\ln\frac{k^*_0+k^*_z}{k^*_0-k^*_z}\,,\qquad dy = \frac{dk^*_z}{k^*_0}\,, \tag{20}$$

According to (20), for given y and $k_\perp$, the values of k^*_z and k^*_0 are given by the formulas:

$$k^*_z = \mu_\perp\sinh y\,,\qquad k^*_0 = \mu_\perp\cosh y\,,\qquad \mu_\perp \equiv \sqrt{k^2_\perp+\mu^2}\,. \tag{21}$$

Then we can calculate $x(y,k_\perp)$ solving the equation (2) with (3) and (4). We find for pions:

$$x = \frac{k^*_z p^* + k^*_0 E^* - \mu^2/2}{k^*_z p^* - k^*_0 E^* + s/2 - 2m^2}\,. \tag{22}$$

and for protons:

$$x = \frac{k^*_z p^* + k^*_0 E^* - m^2}{k^*_z p^* - k^*_0 E^* + s/2 - m^2}\,. \tag{23}$$

Here E^* and p^* are the energy and momentum of the incident proton in the center-of-mass system of NN collision:

$$E^* = \sqrt{s}/2\,,\qquad p^* = \sqrt{s-4m^2}/2\,,\qquad s\equiv s_{NN}\,. \tag{24}$$

In our calculations, we first performed integration over the transverse momentum $k_\perp$, and then over the rapidity y:

$$\langle n\rangle_{\rm pA}\cdot\sigma^{tot}_{\rm pA} = 2\pi\,A\int_{-1}^{-0.5}dy\int_{k^{min}_\perp(y)}^{k^{max}_\perp(y)}dk_\perp\,k_\perp\,f(\,x(y,k_\perp),\,k_\perp)\,. \tag{25}$$

The limits of integration over the transverse momentum $k_\perp$ were specified by setting the minimum and maximum values of the cumulative number under consideration:

$$k^{min}_\perp(y) = k_\perp(y,x_{min})\,,\qquad k^{max}_\perp(y) = k_\perp(y,x_{max})\,, \tag{26}$$

where $k_\perp(y,x)$ is defined by the formulas

$$k_\perp(y,x) = \sqrt{\mu^2_\perp(y,x)-\mu^2}\,,\qquad \mu_\perp(y,x) = \frac{\bar{s}(x)/2}{E^*(x+1)\cosh y + p^*(x-1)\sinh y}\,. \tag{27}$$

The $\bar{s}(x)$ is given by (3) and (4) for pions and for protons.

These limits of integration over transverse momentum $k_\perp$ are of practical interest, since they determine the interval of transverse momenta $k_\perp$ for a given rapidity y, in which particles with given values of the cumulative number must be registered in the experiment. In Table 1 we present them for

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

the production of cumulative pions and protons for two values of the cumulative number x=1.6 and 3.0 and values of rapidity y =-1 and -0.5 for two initial energies $\sqrt{s_{NN}} = 4$ and 8 GeV. From this table we see that at an initial energy of 8 GeV the transverse momenta are approximately two times greater than at 4 GeV (see Figures 1 and 2).

Table 1. The minimal ($k_\perp^{min}$) and maximal ($k_\perp^{max}$) transverse momenta of cumulative pions and protons, Minimum ($k_\perp^{min}$) and maximum ($k_\perp^{max}$) transverse momenta of cumulative pions and protons, corresponding to the values of the cumulative number x = 1.6 and 3.0 for given values of rapidity y and initial energy.

$\sqrt{s_{NN}}$	4 GeV			8 GeV		
	y	$k_\perp^{min}$	$k_\perp^{max}$	y	$k_\perp^{min}$	$k_\perp^{max}$
π	-1.	1.468	2.282	-1.	3.634	5.833
	-0.5	1.876	2.605	-0.5	4.602	6.484
p	-1.	1.549	2.547	-1.	3.691	5.988
	-0.5	2.112	2.952	-0.5	4.728	6.671

The results of our calculations of pion and proton multiplicities using the formula (25) in the new cumulative region at $x \in (1.6, 3.0)$ and $y \in (-1, -0.5)$ (region C in the Figures 1 and 2) for pAu collisions are presented in Table 2. For the dependence of particle yields in the cumulative region on transverse momentum, we used dependences (11) and (14), obtained within the framework of the theoretical approach [16–21] presented in the previous section.

For comparison, we also carried out similar calculations with the Gaussian dependence on transverse momentum (7), used in the original experimental works [9,10], and with the exponential dependence (7), proposed in works [32,34]. The value $x = 1.6$ was chosen as the beginning of the cumulative region, since, starting from this value, the fits used in these works are valid for both pions and protons. For the total cross section of the pAu interaction we used the value $\sigma^{tot}_{\mathrm{pAu}}$=2 bn.

From Table 2 we see that at an initial energy of 4 GeV, the predictions for particle multiplicities obtained within the framework of the described theoretical model are approximately in order of magnitude consistent with the results obtained using both Gaussian and exponential fits of experimental data. At an initial energy of 8 GeV, the results of present theoretical calculations support the results obtained using the more natural exponential fits for the transverse momentum dependence proposed in [32,34], while the use of Gaussian type fits [9,10] predicts extremely low particle multiplicities into this new cumulative region at this energy.

The reason for this is, of course, that at an initial energy of 8 GeV the transverse momenta in the new cumulative region C (see Figures 1 and 2 and Table 1) are approximately two times greater than at 4 GeV .

Table 2. Pion and proton integrated multiplicities in the new cumulative region at $x \in (1.6, 3.0)$ and $y \in (-1, -0.5)$ (region C in the Figures 1 and 2) for pAu collisions calculated with the transverse momentum dependencies (11) and (14), obtained in the theoretical approach [16–21] (Theor) for initial energies 4 and 8 GeV. The same with the Gaussian dependence (7), used in the experimental works [9,10] (Gauss) and with the exponential dependence (7), proposed in works [32,34] (Exponent).

$\sqrt{s_{NN}}$		4 GeV			8 GeV	
$k_\perp$ fit type	Gauss	Exponent	Theor.	Gauss	Exponent	Theor.
$\langle n_\pi \rangle_{\mathrm{pAu}}$	$3{\cdot}10^{-6}$	$9{\cdot}10^{-6}$	$1.1{\cdot}10^{-5}$	$1.4{\cdot}10^{-13}$	$7{\cdot}10^{-7}$	$1.9{\cdot}10^{-6}$
$\langle n_{\mathrm{p}} \rangle_{\mathrm{pAu}}$	$2.4{\cdot}10^{-6}$	$1.5{\cdot}10^{-4}$	$7{\cdot}10^{-5}$	$2{\cdot}10^{-24}$	$1.4{\cdot}10^{-8}$	$5{\cdot}10^{-8}$

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

5. Estimates of cumulative production in the region available for study with NICA MPD.

Using the estimates of the cumulative production in pAu collisions in the rapidity region $-1 < y < -0.5$ (region C in Figures 1 and 2), made in the previous section, we will now try to make a rough estimate of the production of cumulative pions and protons for the symmetric AuAu reaction in the region $0.5 < |y| < 1$ available for study with NICA MPD.

Recall that we have excluded the region near zero rapidity, since the theoretical approach [16–21] (Figure 3), used in the present work to describe the transverse momentum dependence of cumulative production (see Section 3), is not valid at small k_z^* values. Another reason for excluding this region from the present consideration is the fact that in this region it may be important to take into account the contribution of the rarer flucton-flucton scattering process [29–31]. This process, which is of great physical interest, requires a separate special study, which we leave for our future studies. Let us only note that such a process can be studied experimentally only in the new cumulative region of central rapidities and large transverse momenta, available for research using MPD and SPD facilities of NICA collider [26–28], and cannot be studied in the traditional cumulative region of fragmentation of one of the nuclei.

In order to obtain estimates for cumulative particles in the $-1 < y < -0.5$ region in the AuAu reaction, based on estimates of their yields in this region in the pAu collision, it is necessary to take into account the increased effective flux of nucleons compared to protons, which will interact with the flucton in the gold nucleus. Of course, it is also necessary to take into account that in this case there is also a symmetrical contribution to the rapidity region $0.5 < y < 1$, which comes from the interaction of the nucleons of the second nucleus with the flucton of the first nucleus.

Replacing an incident proton with a nucleus increases the number of projectile nucleons interacting with a flucton in another nucleus. To take this into account, we introduce an effective factor γ. The magnitude of this factor can be estimated through the ratio of the number of participating nucleons $\gamma_{part} = \langle N_{part}\rangle_{\text{AuAu}}/\langle N_{part}\rangle_{\text{pAu}}$ or NN collisions $\gamma_{coll} = \langle N_{coll}\rangle_{\text{AuAu}}/\langle N_{coll}\rangle_{\text{pAu}}$ in pAu and AuAu reactions. Clearly, the result will strongly depend on the centrality of the AuAu collision.

At high energies, the values of γ_{part} and γ_{coll} are significantly different. So from the ALICE experiment [36–38] we know that at LHC energies for pPb and PbPb collisions γ_{part}=15 for min.bias events and increases to a value of 24 for 0-5% of the most central events, while γ_{coll} = 55 for min.bias of events, increasing to 115 for central ones. As is known, the number of participating nucleons, N_{part}, is determined mainly by the collision geometry (the value of the impact parameter [39]) and weakly depends on the initial energy, while the number of nucleon-nucleon collisions, N_{coll}, increases significantly with increasing initial energy, therefore, taking into account the relatively low energies of the NICA collider, for further rough estimates we chose the value of γ equal to γ_{part}=15 for the case of min.bias collisions.

The obtained etimates of integral multiplicities and yields of pions and protons in min.bias AuAu collisions at NICA collider in the cumulative region $x \in (1.6, 3.0)$ and $0.5 < |y| < 1$ due to the process of interaction of a nucleon of one nucleus with a flucton of another are presented in Table 3. The contribution of nucleon-flucton interactions was calculated using the dependences on the transverse momentum (11) and (14) obtained in the theoretical approach [16–21] (see Section 3).

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

Table 3. Estimates of integral multiplicities and yields of pions and protons in min.bias AuAu collisions in the new cumulative region $x \in (1.6, 3.0)$ and $0.5 < |y| < 1$ available for study with NICA MPD. The contribution of nucleon-flucton interactions was calculated using the dependences on the transverse momentum (11) and (14) obtained in the theoretical approach [16–21] (see Section 3).

$\sqrt{s_{NN}}$	4 GeV	8 GeV
$\langle n_\pi \rangle_{\rm AuAu}$	$3{\cdot}10^{-4}$	$6{\cdot}10^{-5}$
$\langle n_{\rm p} \rangle_{\rm AuAu}$	$2{\cdot}10^{-3}$	$1.5{\cdot}10^{-6}$
$Y^{\pi}_{\rm AuAu}$	80	1500
$Y^{\rm p}_{\rm AuAu}$	500	40

Estimates of cumulative particle yields,

$$Y_{\rm AuAu} = \langle n \rangle_{\rm AuAu} \cdot R_{\rm AuAu} \cdot t\,, \tag{28}$$

in Table 3 are presented for one hour (t) of operation of the NICA collider. When performing them, we take into account that the design luminosity of the NICA collider for AuAu collisions at an energy of 8 GeV will be 100 times higher than at an energy of 4 GeV - $L_{\rm AuAu}$=10^{27} and 10^{25} $cm^{-2}sec^{-1}$ respectively, resulting in interaction rates,

$$R_{\rm AuAu} = L_{\rm AuAu} \cdot \sigma^{tot}_{\rm AuAu}\,, \tag{29}$$

of 7 kHz and 70 Hz with $\sigma^{tot}_{\rm AuAu}$ ≈7 bn [26,27]. When analyzing the yields of cumulative particles presented in Table 3, it is necessary also to keep in mind that in a real experiment the final number of "good" events that have been selected according to various criteria, such as the position of the interaction vertex, the activation of various triggers, etc., usually turns out to be significant (approximately an order of magnitude) less than that given by general estimates.

From the $Y_{\rm AuAu}$ values in Table 3 we see that the increase in the NICA collider luminosity with increasing initial energy from 4 to 8 GeV practically compensates the overall drop of the integral multiplicities $\langle n \rangle_{\rm AuAu}$, arising due to the general increase of transverse momenta in the cumulative region with energy. This allows us to conclude that it is possible to observe the production of particles in a new cumulative region of central rapidities and high transverse momenta in Au-Au collisions using the MPD installation of the NICA complex both at initial energies of 4 and 8 GeV.

Conducting research at higher energies of the NICA collider (for example, at $\sqrt{s_{NN}}$=11 GeV) will be more difficult, because a further drop in integral multiplicities $\langle n \rangle_{\rm AuAu}$ will no longer be compensated by an increase in luminosity, which remains at the same level at 11 GeV as at 8 GeV [26,27].

To study the dependence of the production of pions and protons on the cumulative number within the described theoretical approach, we also calculated the inclusive cross section

$$\frac{d\sigma}{dx} = \frac{\langle n \rangle^{\Delta x}_{\rm AuAu}}{\Delta x} \sigma^{tot}_{\rm AuAu} \tag{30}$$

characterizing the distribution of cumulative particles in x. The results of the calculations are presented in the Figure 5.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

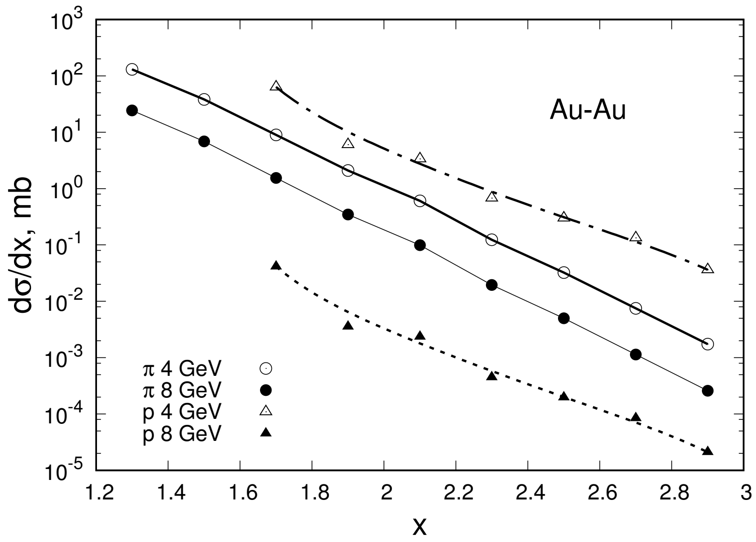

Figure 5. Inclusive cross sections for the production of pions (○,●) and protons (△,▲) in AuAu collisions, integrated over rapidity intervals $0.5 < |y| < 1$ and available for study using NICA MPD, as a function of the cumulative number x, respectively, for two initial energies $\sqrt{s_{NN}} = 4$ and 8 GeV. (Lines serve to guide the eye).

From Table 3 and Figure 5 we see that with increasing initial energy, the proton yield decreases much faster than the pion yield for the same fixed value of the cumulative number x. At 4 GeV the ratio of proton to pion yields is about 10 for the same value of x, but at 8 GeV the pion yield already dominates the proton yield by more than 10 times. Let us recall that in the traditional cumulative region of nucleus fragmentation at low values of transverse momenta, the ratio of proton and pion yields was about 10^4 for the same value of x (see the values of the constants C_{0p} and $C_{0\pi}$ in the paragraph after the formula (6)).

This effect occurs due to different mechanisms of the formation of particles with momentum outside the pp-kinematics - coherent coalescence (recombination) of three flucton quarks for a proton and fragmentation of one flucton quark for a pion in the theoretical approach [16–21] described in Section 3.

There is some experimental indication that such an effect does occur. Results of the SPIN collaboration on the production of protons and pions with large transverse momenta at an angle of 40° on stationary nuclear targets by protons with an energy of 50 GeV/c ($\sqrt{s_{NN}} = 9.8$), which corresponds to the cumulative number x up to 1.2 show [40] that in this region the ratio p/π for the same value of the cumulative number x is of the order of 100, which is significantly less than 10^4, which was the case in traditional cumulative region of nucleus fragmentation.

It is assumed that the obtained dependences will be studied in MPD and SPD experiments at the NICA collider [26–28] using existing and new ultrathin pixel detector systems. It is important that for reliable registration of very rare events of particle creation in the cumulative region and reliable separation of their tracks from various kinds of false background tracks, it is necessary to have a signal simultaneously from several types of detectors used by the installation. In this regard, information from the internal tracking system is especially important, making it possible to reliably confirm the exit of the track of a cumulative particle from the vertex of the primary interaction, and thus isolate it from the inevitable noise background.

6. Conclusion

A consequence of the presence of nuclear density fluctuations in colliding nuclei - the so-called fluctons [3] - is the production of particles with momentum in the region outside the nucleon-nucleon kinematics, called cumulative [4]. From the modern point of view, these multinucleon fluctons occasionally appearing in nuclei are clumps of dense cold baryon-enriched quark-gluon matter.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

Therefore, studying the process of nucleon scattering on such nuclear density fluctuations with the production of a particle in the cumulative region is of great interest.

In this work, we estimate the yields of pions and protons, due to the interaction of one of the nucleons of a nucleus with a flucton in another nucleus, in the new cumulative region of central rapidities and large transverse momenta, available for study at the MPD and SPD facilities of the NICA collider [26–28].

Calculations were carried out using a previously developed microscopic approach [16–21], which allows us to describe dependence of particle yields on transverse momentum at different values of the cumulative number simultaneously for both pions and protons using a single parameter - the mass of the constituent quark m_q = 310 MeV.

It is shown that the found value of pion and proton yields in this new cumulative region indicates the possibility of studying this phenomenon in collisions of heavy nuclei at the MPD facility of the NICA complex at low initial energies of 4 - 8 GeV.

Theoretical calculations also predict that in this region of initial energies, when going from 4 to 8 GeV, the dominance of proton yields over pions is replaced by dominance of pion yields. This effect arises due to different mechanisms of particle formation in the interaction of a nucleon with a flucton within the framework of the used theoretical approach [16–21] - fragmentation of one flucton quark for pion production and coherent fusion (recombination) of three flucton quarks for proton production (see Section 3).

However, when making these conclusions, it is necessary to keep in mind that in this work only the contribution of the interaction of a nucleon with a flucton was taken into account and the rarer process of flucton-flucton scattering [29**?** ,30] was not taken into account, which, however, can make a significant contribution especially in the region of the most central rapidities $|y| < 0.5$. The process of interaction of fluctons is of great physical interest and requires a separate special study, which we leave for our future research. It is important that this process can be studied experimentally only in the new cumulative region of central rapidities and large transverse momenta, available for research at the MPD and SPD facilities of the NICA collider, and cannot be studied in the traditional cumulative region of fragmentation of one of the nuclei.

7. Summary

The production of particles outside the region allowed by the kinematics of nucleon-nucleon collision is calculated due to interactions involving dense cold clusters of quark-gluon matter in nuclei. Calculations were carried out using a previously developed microscopic approach [16–21], which makes it possible to describe dependence of particle yields on transverse momentum at different values of the cumulative number simultaneously for both pions and protons using a value of 310 MeV for a single parameter, the mass of the constituent quark.

Based on these calculations the possibility of observing this process in the region of central rapidities and large transverse momenta in collisions of heavy ions at low energies at the MPD facility of the NICA collider complex has been demonstrated.

The theoretical calculations also predict in this region an increasing dominance of pion yields over protons as the initial energy of nuclear collisions increases from 4 to 8 GeV, due to different mechanisms of their formation.

Acknowledgments: The research was supported by the RSF project 23-12-00042.

Conflicts of Interest: The author declares no conflict of interest.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

Abbreviations

The following abbreviations are used in this manuscript:

NICA	Nuclotron-based Ion Collider fAcility
MPD	Multi Purpose Detector
SPD	Spin Physics Detector
JINR	Joint Institute for Nuclear Research
FAIR	Facility for Antiproton and Ion Research
ALICE	A Large Ion Collider Experiment
LHC	Large Hadron Collider
RHIC	Relativistic Heavy Ion Collider

References

1. Leksin G.A. Elastic and Quasi-Elastic Scattering of 660 MeV Protons by Deuterons. *Sov. Phys. JETP* **1957**, *5*, 371–377.
2. Azhgirei L.S., Vzorov I.K., Zrelov V.P., Meshcheriakov M.G., Neganov B.S., Shabudin A.F. Knockout of Deuterons from Li, Be, C, and O Nuclei by Protons of Energy 675 MeV. *Sov. Phys. JETP* **1958**, *6*, 911–919.
3. Blokhintsev D.I. On the Fluctuations of Nuclear Matter. *Sov. Phys. JETP* **1958**, *6*, 995–999.
4. Baldin A.M., Gerasimov S.B., Guiordenescu H., Zubarev V.N., Ivanova L.K., Kirillov A.D., Kuznetsov V.A., Moroz N.S., Radomanov V.B., Ramzhin V.N., Stavinskii V.S., Yatsuta M.I. Cumulative meson production. *Sov. J. Nucl. Phys.* **1974**, *18*, 41–44.
5. Papp J., Jaros J., Schroeder L., Staples J., Steiner H., Wagner A., Wiss J. Inclusive Pion Production in Collisions of Relativistic Protons, Deuterons, Alphas, and Carbon Ions with Nuclei. *Phys. Rev. Lett.* **1975**, *34*, 601–604.
6. Baldin A.M., Bondarev V.K., Giordenescu N., Golovanov L.B., Mazarsky V.L., Manyatovsky A.N., Moroz N.S., Panebrattsev Yu.A. , Pentsya, M. , Povtoreiko, A.A., Rikhvitsky S.V., Stavinsky V.S., Khrenov A.N., Tsvinev A.P. Experimental Data on Cumulative Pion Production at 8.9-GeV/c Proton Interaction with Light Nuclei. **1982**, *Preprint JINR-1-82-28*.
7. Ableev V.G., Abdushukurov D.A., Avramenko S.A., Dimitrov Ch., Filipkowski A., Kobushkin A.P., Nikitin D.K., Nomofilov A.A., Piskunov N.M., Sharov V.I., Sitnik I.M., Strokovsky E.A., Strunov L.N., Vizireva L. Vorobiev G.G., Zaporozhets S.A. A study of the proton momentum spectrum from deuteron fragmentation at 8.9 GeV/c and an estimate of admixture parameters for the six-quark state in the deuteron. *Nucl. Phys. A* **1983**, *393*, 491–501.
8. Boyarinov, S.V. et. al., The properties of nuclear matter at small distances, *Sov. J. Nucl. Phys.* **1992**, *55*, 917-921.
9. Boyarinov, S.V. et. al., Production of Cumulative Protons at Momenta 0.6 GeV/c to 1.83 GeV/c, *Sov. J. Nucl. Phys.* **1987**, *46*, 871–876.
10. Boyarinov, S.V. et. al., Yields of p, anti-p, pi+-, and K+- emitted at an angle of 97 degrees in the laboratory system from nuclei irradiated by 10.14 GeV protons, *Phys. Atom. Nucl.* **1994**, *57*, 1379–1388.
11. Efremov A. V., Quark-parton picture of the cumulative production, *Progress in Particle and Nuclear Physics* **1982** *8* 345–365.
12. Burov V.V., Lukyanov V.K., and Titov A.I., Large momentum pion production in proton nucleus collisions and the idea of fluctuons in nuclei, *Phys. Lett. B* **1977** *67* 46-48.
13. Schmidt I.A., Blankenbecler R. Relativistic interactions between nuclei. *Phys. Rev. D* **1977**, *15*, 3321–1326.
14. Frankfurt L.L. and Strikmann M.I., High-energy phenomena, short-range nuclear structure and QCD, *Phys. Rep.* **1981** *76* 215-347.
15. Efremov A.V., Kaidalov A.B., Kim V.T., Lykasov G.L., Slavin N.V. Production of cumulative hadrons in quark models of flucton fragmentation. *Sov. J. Nucl. Phys.* **1988**, *47*, 868-874.
16. Braun M.A., Vechernin V.V. Nuclear Structure Functions and Particle Production in the Cumulative Region in the Parton Model. *Nucl. Phys. B* **1994**, *427*, 614–640.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

17. Braun M.A., Vechernin V.V. Structure Functions and Particle Production in the Cumulative Region: two different exponentials. *Phys. Atom. Nucl.* **1997**, *60*, 432–438.
18. Braun M.A., Vechernin V.V. Transverse-momentum dependence of cumulative pions. *Phys. Atom. Nucl.* **2000**, *63*, 1831–1834.
19. Braun M.A., Vechernin V.V. Production of cumulative hadrons in quark models of flucton fragmentation. *Nucl. Phys. B - Proc. Suppl.* **2001**, *92*, 156–161.
20. Braun M.A., Vechernin V.V. Quark coalescence mechanism near the threshold. *Theor. Math. Phys.* **2004**, *139*, 766–786.
21. Vechernin V. Transverse momentum dependence of spectra of cumulative particles produced from droplets of dense nuclear matter. *AIP Conf. Proc.* **2016**, *1707*, 060020.
22. Gorenstein M.I., Zinovjev G.M., Cluster model of cumulative particle production in hadron-nucleus collisions, *Phys. Lett. B* **1977**, *67*, 100-102.
23. Bogatskaya I.G., Chiu C.B., Gorenstein M.I., and Zinovjev G.M., Fireball model for baryonic inclusive spectra in particle-nucleus and nuclei-nucleus collisions at high energy. *Phys. Rev. C* **1980**, *22*, 209-220.
24. Anchishkin D.V., Gorenstein M.I., and Zinovjev G.M., Cumulative effect and the model of nuclear fireballs. *Phys. Lett. B* **1982**, *108*, 47-50.
25. Motornenko A., Gorenstein M.I., Cumulative production of pions by heavy baryonic resonances in proton-nucleus collisions. *Journal of Physics G* **2017**, *44*, 025105.
26. Kekelidze V., Kovalenko A., Lednicky R., Matveev V., Meshkov I., Sorin A., Trubnikov G. Feasibility study of heavy-ion collision physics at NICA JINR. *Nucl. Phys. A* **2017**, *967*, 884–887.
27. Kekelidze V., Matveev V., Meshkov I., Sorin A., Trubnikov G. Project Nuclotron-based Ion Collider Facility at JINR. *Physics of Particles and Nuclei* **2017**, *48*, 727–741.
28. Abazov V.M. et al. [The SPD collaboration] Conceptual design of the Spin Physics Detector **2022**, *arXiv:2102.00442v3 [hep-ex]*.
29. Denisovskaya O., Mikhailov K., Polozov P., Prokudin M., Sharkov G., Stavinsky A., Stolin V., Tolochek R., Tolstoukhov S. Dense Cold Nuclear Matter Study with Cumulative Trigger. Proposal. **2009**, *arXiv:0911.1658*.
30. Alekseev I.G., Vishnyakov V.E., Golutvin A.I., Goryachev V.S., Dzubenko G.B., Dolgolenko A.G., Zagreev B.V., Kiselev S.M., Korolko I.E., Leksin G.A., Mikhaylov K.R., Polozov P.A., Prokudin M.S., Svirida D.N., Stavinsky A.V., Stolin V.L., Sharkov G.B. Measurement of cumulative-photon spectra at high transverse momenta in $^{12}C^{9}Be$ interactions at an energy of 3.2 GeV per nucleon. *Phys. Part. Nuclei* **2008**, *71*, 1848–1859.
31. Stavinskiy A. Dense Cold Matter with Cumulative Trigger. *Phys. Part. Nucl. Lett.* **2011**, *8*, 912–914.
32. Vechernin V.V. Clusters of cold dense nuclear matter and their registration with the MPD vertex detector. *Phys. Part. Nuclei* **2021**, *52*, 604–608.
33. Zherebchevsky V.I., Kondratiev V.P., Vechernin V.V., Igolkin S.N. The concept of the MPD vertex detector for the detection of rare events in Au+Au collisions at the NICA collider. *Nuclear Inst. and Methods in Physics Research A* **2021**, *985*, 164668.
34. Vechernin V.V. Yield of particles in the cumulative region at central rapidities and large transverse momenta at the NICA collider. *Phys. Part. Nuclei* **2022**, *53*, 433–440.
35. Vechernin V.V. Correlation of Cumulative Particle Production with Strange and Heavy-Flavor Particle Yields in the String Fusion Model. *Phys. Part. Nuclei* **2023**, *54*, 528–535.
36. B. Abelev et al. (ALICE Collaboration). Centrality determination of Pb-Pb collisions at 2.76 TeV with ALICE *Phys. Rev. C* **2013**, *88*, 044909.
37. J. Adam et al. (ALICE Collaboration). Centrality dependence of particle production in p-Pb collisions at 5.02 TeV *Phys. Rev. C* **2015**, *91*, 064905.
38. Loizides C.; Kamin J.; d'Enterria D. Improved Monte Carlo Glauber predictions at present and future nuclear colliders, *Phys. Rev. C* **2019**, *99*, 019901.

Preprints (www.preprints.org) | NOT PEER-REVIEWED | Posted: 6 December 2023 doi:10.20944/preprints202312.0300.v1

39. Vechernin, V.V.; Nguyen H.S. Fluctuations of the number of participants and binary collisions in AA interactions at fixed centrality in the Glauber approach. *Phys. Rev. C* **2011**, *84*, 054909.
40. Semak A., High pt anti-proton and meson production in cumulative pA reaction at 50 GeV/c, reported at *the LXX International Conference "NUCLEUS–2020. Nuclear physics and elementary particle physics. Nuclear physics technologie"*, St.Petersburg, October 11-17, **2020**. https://indico.cern.ch/event/839985/contributions/3983657 /attachments/2124000/3576745/NUCLEUS_2020_Semak.pdf

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.