Transient state of matter in hadron and nucleus collisions

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Abstract

We discuss properties of the specific strongly interacting transient collective state of matter in hadron and nuclei reactions and emphasize similarity in their dynamics. We consider elliptic flow introduced for description of nucleus collisions and discuss its possible behavior in hadronic reactions due to rotation of the transient matter.

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Introduction

Multiparticle production in hadron and nucleus collisions and corresponding observables provide a clue to the mechanisms of confinement and hadronization. Discovery of the deconfined state of matter has been announced by four major experiments at RHIC \cite{1}. Despite the highest values of energy and density have been reached, a genuine quark-gluon plasma QGP (gas of the free current quarks and gluons) was not found. The deconfined state reveals the properties of the perfect liquid, being strongly interacting collective state and therefore it was labelled as sQGP \cite{2}. These results immediately have became a subject for an active theoretical studies. The nature of this new form of matter is not known and the variety of models has been proposed to treat its properties \cite{3}. The importance of this result is that the matter is still strongly correlated and reveals high degree of the coherence when it is well beyond the critical values of density and temperature. The elliptic flow and constituent quark scaling of the observable $v_2$ demonstrated an importance of the constituent quarks \cite{4} and their role as effective degrees of freedom of the newly discovered form of matter. Generally speaking this result has shown an importance of the nonperturbative effects in the region where such effects were not expected. Review paper which provides an emphasis on the historical aspects of the QGP searches was published in \cite{5}. The important conclusion made in this paper is that the deconfined state of matter has already been observed in hadronic reactions and it would be interesting to study collective properties of transient state in reactions with hadrons and nuclei simultaneously.

In this paper we also note that the behavior of collective observables in hadronic and nuclear reactions could have similarities. We discuss the role of the coherent rotation of the transient matter in hadron and nuclei reactions and dependence of the anisotropic flows.

1 Experimental probes of collective dynamics. Constituent quark scaling.

There are several experimental probes of collective dynamics in \textit{AA} interactions \cite{6,8}. A most widely discussed one is the elliptic flow

$$v_2(p_\perp) \equiv \langle \cos(2\phi) \rangle_{p_\perp} = \langle \frac{p_x^2 - p_y^2}{p_\perp^2} \rangle,$$

(1)

which is the second Fourier moment of the azimuthal momentum distribution of particles at fixed value of $p_\perp$. The common origin of the elliptic flow is considered to be an almond shape of the overlap region of the two spherically symmetrical...
colliding nuclei and strong interaction in this region. The azimuthal angle $\phi$ is the angle of the detected particle with respect to the reaction plane, which is spanned by the collision axis $z$ and the impact parameter vector $b$. The impact parameter vector $b$ is directed along the $x$ axis. Averaging is taken over large number of the events. Elliptic flow can be expressed in covariant form in terms of the impact parameter and transverse momentum correlations as follows

$$v_2(p_\perp) = \frac{\langle \hat{b} \cdot p_\perp \rangle^2}{p_\perp^2} - \frac{\langle \hat{b} \times p_\perp \rangle^2}{p_\perp^2},$$  \hspace{1cm} (2)$$

where $\hat{b} \equiv b/b$. In more general terms, the momentum anisotropy $v_n$ can be characterized according to the Fourier expansion of the freeze-out source distribution \[8\]:

$$S(x, p_\perp, y) \equiv dN/d^4xd^2p_\perp dy \hspace{1cm} (3)$$

in terms of the momentum azimuthal angle.

The observed elliptic flow $v_2$ is the weighted average of $v_2(x, p_\perp, y)$ defined in the infinitesimal spacetime volume $d^4x$. Common explanation of the dynamical origin of elliptic flow is the strong scattering during the early stage of interaction in the overlap region.

There is an extensive set of the experimental data for the elliptic flow $v_2$ in nucleus-nucleus collisions (see for the recent review, e.g. \[10\]). Integrated elliptic flow $v_2$ has a nontrivial dependence on $\sqrt{s_{NN}}$: at low energies it demonstrates sign-changing behavior, while at high energies $v_2$ is positive and increases with $\sqrt{s_{NN}}$ linearly.

The differential elliptic flow $v_2(p_\perp)$ increases with $p_\perp$ at small values of transverse momenta, then it becomes flatten in the region of the intermediate transverse momenta and decreases at large $p_\perp$, but to a non-zero value. The magnitude of $v_2$ in the region of intermediate $p_\perp$ is rather high at RHIC and has a value about 0.2 close to hydrodynamical limit \[10\] indicating presence of order and pair correlations relevant for the liquid phase. The increase of elliptic flow at small transverse momenta is in a good agreement with hydrodinamical model while the experimental data deviate from this model at higher values of transverse momenta \[11\].

An interesting property of the differential elliptic flow $v_2(p_\perp)$ in $AA$-collisions — the constituent quark scaling \[4\]. We discuss it in a some detail now. The scaling occurs if hadronization mechanism goes via coalescence of the constituent quarks and it is expressed as an approximate relation $v_2(p_\perp) \simeq n_V v_2(p_\perp/n_V)$, where $n_V$ is the number of the valence constituent quarks in the hadron. This scaling takes place in the region of the intermediate transverse momenta and reveals important role of constituent quarks in the deconfined phase reached in nucleus collisions \[12\]. The quantity $v_2/n_V$ can be interpreted as an elliptic flow of a constituent quark $v_2^Q$. It increases with transverse momentum in the region.
$0 \leq p^Q_\perp \leq 1 \text{ GeV}/c$ and with a rather good accuracy does not depend on $p^Q_\perp$ at $p^Q_\perp \geq 1 \text{ GeV}/c$.

In the following section we will discuss energy and transverse momentum dependencies of $v_2$ in hadron collisions at fixed impact parameters and extend this consideration for nucleus collisions with emphasis on the similarity of the transient states in hadron and nucleus collisions. We consider non-central hadron collisions and apply notions acquired from heavy-ion studies. It is reasonable to do so in the framework of the constituent quark model picture for hadron structure where hadrons look similar to the light nuclei. In particular, we amend the model [13] for hadron interactions based on the chiral quark model ideas and consider the effect of collective rotation of the quark matter in the overlap region. All that was said above might have a particular interest under studies of hadron collisions in the new few TeV energy region where number of secondary particles will increase significantly indicating importance of collective effects.

## 2 Transient state of matter in hadron collisions

In principle, the geometrical picture of hadron collision is in complete analogy with nucleus collisions and we believe that the assumption [16] on the possibility to determine reaction plane in the non-central hadronic collisions can be justified experimentally and the standard procedure[17] can be used. It would be useful to perform the measurements of the characteristics of multiparticle production processes in hadronic collisions at fixed impact parameter by selecting specific events sensitive to its value and direction. The relationship of the impact parameter with the final state multiplicity is a useful tool in these studies similar to the studies of the nuclei interactions, e.g in the Chou-Yang approach [15] one can restore the values of impact parameter from the charged particle multiplicity [18]. Thus, the impact parameter can be determined through the centrality [19] and then, e.g. elliptic flow, can be analyzed selecting events in a specific centrality ranges. Indeed, in the work [19] the following relation

$$c(N) \simeq \frac{\pi b^2(N)}{\sigma_{inel}},$$

for the values of the impact parameter $b < \bar{R}$ can be extended straightforwardly to the case of hadron scattering. Then we should consider $\bar{R}$ as a sum of the two radii of colliding hadrons and $\sigma_{inel}$ as the total inelastic hadron-hadron cross-section. The centrality $c(N)$ is the centrality of the events with the multiplicity larger than $N$ and $b(N)$ is the impact parameter where the mean multiplicity $\bar{n}(b)$ is equal to $N$. The centrality can be determined by the fraction of the events with the largest number of produced particles which are registered by detectors [19, 20].

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Of course, the standard inclusive cross-section for unpolarized particles being integrated over impact parameter $b$, cannot depend on the azimuthal angle of the detected particle transverse momentum. We need to be a more specific at this point and consider for discussion of the azimuthal angle dependence some particular form for the inclusive cross-section. For example, with account for $s$–channel unitarity inclusive cross-section can be written in the following form

$$
\frac{d\sigma}{d\xi} = 8\pi \int_0^\infty bdb \frac{I(s, b, \xi)}{|1 - iU(s, b)|^2}.
$$

(5)

Here the function $U(s, b)$ is similar to an input Born amplitude and related to the elastic scattering scattering amplitude through an algebraic equation which enables one to restore unitarity [21]. The set of kinematic variables denoted by $\xi$ describes the state of the detected particle. This function is constructed from the multiparticle analogs $U_n$ of the function $U$ and is in fact an inclusive cross-section in the impact parameter space without account for the unitarity corrections, which are given by the factor

$$
w(s, b) \equiv |1 - iU(s, b)|^{-2}
$$

in Eq. (5). Unitarity, as it will be evident from the following, modifies anisotropic flow. When the impact parameter vector $b$ and transverse momentum $p_\perp$ of the detected particle are fixed, the function $I = \sum_{n \geq 3} I_n$, where $n$ denotes a number of particles in the final state, depends on the azimuthal angle $\phi$ between vectors $b$ and $p_\perp$. It should be noted that the impact parameter $b$ is the variable conjugated to the transferred momentum $q \equiv p'_a - p_a$ between two incident channels which describe production processes of the same final multiparticle state. The dependence on the azimuthal angle $\phi$ can be written in explicit form through the Fourier series expansion

$$
I(s, b, y, p_\perp) = \frac{1}{2\pi} I_0(s, b, y, p_\perp)[1 + \sum_{n=1}^\infty 2\bar{v}_n(s, b, y, p_\perp) \cos n\phi].
$$

(6)

The function $I_0(s, b, \xi)$ satisfies to the following sum rule

$$
\int I_0(s, b, y, p_\perp)dp_\perp dy = \bar{n}(s, b)\text{Im}U(s, b),
$$

(7)

where $\bar{n}(s, b)$ is the mean multiplicity depending on impact parameter. Thus, the bare flow $\bar{v}_n(s, b, y, p_\perp)$ is related to the measured flow $v_n$ as follows

$$
v_n(s, b, y, p_\perp) = w(s, b)\bar{v}_n(s, b, y, p_\perp).
$$

In the above formulas the variable $y$ denotes rapidity, i.e. $y = \sinh^{-1}(p/m)$, where $p$ is a longitudinal momentum. Thus, we can see that unitarity corrections
are mostly important at small impact parameters, i.e. they modify flows at small centralities, while peripheral collisions are almost not affected by unitarity. The following limiting behavior of \( v_n \) at \( b = 0 \) can be easily obtained:

\[
v_n(s, b = 0, y, p_{\perp}) \to 0
\]

at \( s \to \infty \) since \( U(s, b = 0) \to \infty \) in this limit.

General considerations demonstrate that we could expect significant values of directed \( v_1 \) and elliptic \( v_2 \) flows in hadronic interactions. For example, according to the uncertainty principle we can estimate the value of \( p_x \) as \( 1/\Delta x \) and correspondingly \( p_y \sim 1/\Delta y \) where \( \Delta x \) and \( \Delta y \) characterize the size of the region where the particle originate from. Taking \( \Delta x \sim R_x \) and \( \Delta y \sim R_y \), where \( R_x \) and \( R_y \) characterize the sizes of the almond-like overlap region in transverse plane, we can easily obtain proportionality of \( v_2 \) to the eccentricity of the overlap region, i.e.

\[
v_2(p_{\perp}) \sim \frac{R_y^2 - R_x^2}{R_x^2 + R_y^2}.
\]

(8)

The presence of correlations of impact parameter vector \( b \) and \( p_{\perp} \) in hadron interactions follows also from the relation between impact parameters in the multiparticle production\[9\]:

\[
b = \sum_i x_i \tilde{b}_i.
\]

(9)

Here \( x_i \) stand for Feynman \( x_F \) of \( i \)-th particle, the impact parameters \( \tilde{b}_i \) are conjugated to the transverse momenta \( \tilde{p}_{i,\perp} \). Such correlation should be more prominent in the large-\( x_F \) (fragmentation) region\[1\].

The above considerations are based on the uncertainty principle and angular momentum conservation, but they do not preclude an existence of the dynamical description in the terms similar to the ones used in heavy-ion collisions, i.e. the underlying dynamics could be the same as the dynamics of the elliptic flow in nuclei collisions and transient state can originate from the nonperturbative sector of QCD.

We would like to point out to the possibility that the transient state in both cases can be related to the mechanism of spontaneous chiral symmetry breaking (\( \chi \)SB) in QCD \[23\], which leads to the generation of quark masses and appearance of quark condensates. This mechanism describes transition of current into constituent quarks, which are the quasiparticles with masses comparable to a hadron mass scale. The gluon field is responsible for providing quarks masses and internal structure through the instanton mechanism of the spontaneous chiral symmetry breaking \[24\].

\[1\] It should be noted that the directed flow \( v_1(p_{\perp}) \equiv \langle \cos \phi \rangle_{p_{\perp}} = \langle \hat{b} \cdot p_{\perp}/p_{\perp} \rangle \) the measurements at RHIC \[7\] are in agreement with the above conclusion.
Collective excitations of the condensate are the Goldstone bosons and the constituent quarks interact via exchange of the Goldstone bosons; this interaction is mainly due to a pion field [25]. The general form of the effective Lagrangian (\( \mathcal{L}_{QCD} \rightarrow \mathcal{L}_{\text{eff}} \)) relevant for description of the non-perturbative phase of QCD proposed in [26] and includes the three terms

\[
\mathcal{L}_{\text{eff}} = \mathcal{L}_\chi + \mathcal{L}_I + \mathcal{L}_C.
\]

Here \( \mathcal{L}_\chi \) is responsible for the spontaneous chiral symmetry breaking and turns on first. To account for the constituent quark interaction and confinement the terms \( \mathcal{L}_I \) and \( \mathcal{L}_C \) are introduced. The \( \mathcal{L}_I \) and \( \mathcal{L}_C \) do not affect the internal structure of the constituent quarks.

The picture of a hadron consisting of constituent quarks embedded into quark condensate implies that overlapping and interaction of peripheral clouds occur at the first stage of hadron interaction. At this stage the part of the effective lagrangian \( \mathcal{L}_C \) is turned off (it is turned on again in the final stage of the reaction). Nonlinear field couplings transform then the kinetic energy to internal energy and mechanism of such transformations was discussed by Heisenberg [27] and Carruthers [28]. As a result the massive virtual quarks appear in the overlapping region and some effective field is generated. This field is generated by \( \bar{Q}Q \) pairs and pions strongly interacting with quarks. Pions themselves are the bound states of massive quarks. This part of interaction is described by \( \mathcal{L}_I \) and a possible form of \( \mathcal{L}_I \) was discussed in [29].

The generation time of the effective field (transient phase) \( \Delta t_{\text{eff}} \)

\[
\Delta t_{\text{eff}} \ll \Delta t_{\text{int}},
\]

where \( \Delta t_{\text{int}} \) is the total interaction time. This assumption on the almost instantaneous generation of the effective field has obtained support in the very short thermalization time revealed in heavy-ion collisions at RHIC [30].

Under construction of particular model [13] for the function \( U(s,b) \) it was supposed that the valence quarks located in the central part of a hadron were scattered in a quasi-independent way by the effective field. In accordance with the quasi-independence of valence quarks the basic dynamical quantity is represented in the form of the product [13] of factors \( \langle f_Q(s,b) \rangle \) which correspond to the individual quark scattering amplitudes which are integrated over transverse position distribution of \( Q \) inside its parent hadron and the longitudinal momentum distribution carried by quark \( Q \). The integrated amplitude \( \langle f_Q(s,b) \rangle \) describes averaged elastic scattering of a single valence quark \( Q \) in the effective field, its interaction radius is determined by the quark mass:

\[
R_Q = \xi/m_Q.
\]
Factorization in the impact parameter representation reflects the coherence in the valence quark scattering, it corresponds to the simultaneous scattering of valence quarks by the effective field. This mechanism resembles Landshoff mechanism of the simultaneous quark–quark independent scattering [22]. However, in our case we suppose validity of the Hartree–Fock approximation for the constituent quark scattering in the mean field. Thus, $U$-matrix is a product of the averaged single quark scattering amplitudes, but the resulting $S$-matrix cannot be factorized and therefore the term quasi-independence is relevant. The above picture assumes deconfinement at the initial stage of the hadron collisions and generation of common for both hadrons mean field during the first stage. Those notions were used in the model [13] which has been applied to description of elastic scattering. Here we will extend them to particle production with account of the geometry of the region where the effective field (quarks interacting by pion exchange) is located and conservation of angular momentum.

To estimate the number of scatterers in the effective field one could assume that part of hadron energy carried by the outer condensate clouds is being released in the overlap region to generate massive quarks. Then this number can be estimated by:

$$\tilde{N}(s, b) \propto \frac{(1 - \langle k_Q \rangle) \sqrt{s}}{m_Q} D_{C}^{h_1} \otimes D_{C}^{h_2} \equiv N_0(s) D_{C}(b), \quad (11)$$

where $m_Q$ – constituent quark mass, $\langle k_Q \rangle$ – average fraction of hadron energy carried by the valence constituent quarks. Function $D_{C}^{h}$ describes condensate distribution inside the hadron $h$, and $b$ is an impact parameter of the colliding hadrons. In elastic scattering the massive virtual quarks are transient ones: they are transformed back into the condensates of the final hadrons. The overlap region, which described by the function $D_{C}(b)$, has an ellipsoidal form similar to the overlap region in the nucleus collisions (Fig. 1).

Valence constituent quarks would excite a part of the cloud of the virtual massive quarks and those quarks will subsequently hadronize and form the multi-particle final state. Existence of the massive quark-antiquark matter in the stage preceding hadronization seems to be supported by the experimental data obtained at CERN SPS and RHIC (see [14] and references therein)

The geometrical picture of hadron collision discussed above implies that the generated massive virtual quarks in overlap region carries large orbital angular momentum at high energies and non-zero impact parameters. The total orbital angular momentum can be estimated as follows

$$L \simeq \alpha b \frac{\sqrt{s}}{2} D_{C}(b), \quad (12)$$
where parameter $\alpha$ is related to the fraction of the initial energy carried by the condensate clouds which goes to rotation of the quark system. Due to strong interaction between quarks this orbital angular momentum leads to the coherent rotation of the quark system located in the overlap region as a whole in the $xz$-plane (Fig. 2). This rotation is similar to the liquid rotation where strong correlations between particles momenta exist. This point is different from the parton picture used in [31], where collective rotation of a parton system as a whole was not anticipated. This is a main point of the proposed mechanism of the elliptic flow in hadronic collisions — collective rotation of the strongly interacting system of massive virtual quarks. Number of the quarks in this system is proportional to $N_0(s)$ and it is natural to expect therefore that the integrated elliptic flow $v_2 \propto \sqrt{s}$. Such dependence of $v_2$ is in a good agreement with experimental data for nucleus collisions and this implies already mentioned similarity between hadron and nucleus reactions. The same origin, i.e. proportionality to the quark number in the transient state, has the preasymptotic increase of the total cross-sections [32].

$$\sigma_{tot}(s) = a + b\sqrt{s}$$

in the region up to $\sqrt{s} \sim 0.5 \ TeV$. At higher energies unitarity transforms such dependence into $\ln^2 s$.

We consider now effects of rotation for the differential elliptic flow $v_2(p_\perp)$. We would like to recall that the assumed particle production mechanism is the
Figure 2: Collective rotation of the overlap region, view in the $xz$-plane.

excitation of a part of the rotating cloud of the virtual massive constituent quarks by the one of the valence constituent quarks with subsequent hadronization.

Different mechanisms of the hadronization will be discussed later, and now we will concentrate on the differential elliptic flow $v_2^Q(p_\perp)$ for constituent quarks. It is natural to suppose that the size of the region where the virtual massive quark $Q$ is knocked out from the cloud is determined by its transverse momentum, i.e. $\bar{R} \simeq 1/p_\perp$. However, it is evident that $\bar{R}$ cannot be larger than the interaction radius of the valence constituent quark $R_Q$ which interacts with the massive virtual quarks from the cloud. It is also clear that $\bar{R}$ cannot be less than the geometrical size of the valence constituent quark $r_Q$. The magnitude of the quark interaction radius was obtained under analysis of elastic scattering \[13\] and has the following dependence on the valence constituent quark mass in the form \[10\], where $\xi \simeq 2$ and therefore $R_Q \simeq 1 \text{ fm}$, while the geometrical radius of quark $r_Q$ is about $0.2 \text{ fm}$. The size of the region\footnote{For simplicity we suppose that this region has a spherically symmetrical form} which is responsible for the small-$p_\perp$ hadron production is large, valence constituent quark excites rotating cloud of quarks with various values and directions of their momenta in that case. Effect of rotation will be smeared off in the volume $V_{\bar{R}}$ and therefore $\langle \Delta p_x \rangle_{V_{\bar{R}}} \simeq 0$ (Fig. 3, left panel). Thus,

$$v_2^Q(p_\perp) \equiv \langle v_2 \rangle_{V_{\bar{R}}} \simeq 0 \quad (14)$$

at small $p_\perp^Q$. When we proceed to the region of higher values of $p_\perp^Q$, the radius $\bar{R}$ is decreasing and the effect of rotation becomes more and more prominent, valence quark excites now the region where most of the quarks move coherently, i.e. in the same direction, with approximately the same velocity (Fig. 3, right panel). The
mean value $\langle \Delta p_x v_R \rangle > 0$ and

$$v_2^Q(p_\perp) \equiv \langle v_2^Q \rangle v_R > 0$$

and increase with increasing $p_\perp$. However, as was already mentioned $\bar{R}$ cannot be smaller than the geometrical radius of constituent quark and therefore the increase of $v_2^Q$ with $p_\perp^Q$ will disappear when $\bar{R} = r_Q$, i.e. at $p_\perp^Q \geq 1/r_Q$, and saturation will take place. The value of transverse momentum where the saturation starts is about 1 GeV/c for $r_Q \simeq 0.2 \text{ fm}$. Thus, the qualitative dependence of $v_2^Q(p_\perp)^3$ will have a form depicted in Fig. 4.

Figure 4: Qualitative dependence of the elliptic flow $v_2^Q$ of constituent quarks on transverse momentum.

Predictions for the elliptic flow for the particular hadron depends on the supposed mechanism of hadronization. For the region of the intermediate values of

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3It is worth to note that the subscript $Q$ is used for the incoming constituent quark, while the superscript $Q$ being used for the outgoing constituent quarks
$p_{\perp}$ the constituent quark coalescence mechanism \cite{4} would be dominating one. In that case values for hadron elliptic flow can be obtained from the constituent quark one by the replacement $v_2 \to n_V v_Q^2$ and $p_{\perp} \to p_{Q\perp}^2/n_V$.

However, the fragmentation mechanism should also be present at small and large transverse momenta, and it will survive at large $p_{\perp}$. As a possible choice for the fragmentation mechanism, the chiral quark models can be used and it implies that the virtual massive quark $Q$ fluctuates into Goldstone boson and another constituent quark $Q'$ \cite{33}:

$$Q \to GB + Q',$$

where $GB$ denotes Goldstone bosons (Fig. 5).

\begin{figure}[ht]
\centering
\includegraphics[width=0.4\textwidth]{fig5.png}
\caption{Schematical view of the quark fragmentation into $\pi^0$ in the chiral quark models.}
\end{figure}

Elliptic flow of the quarks and elliptic flow of the hadron are approximately equal for the fragmentation process. Thus, in the region of the intermediate transverse momenta elliptic flow of quarks will be enhanced due to quark coalescence and at higher transverse momenta the elliptic flow will level off and return to the flat dependence of the quark elliptic flow (Fig. 4).

The considered mechanism of particle production has a two-step nature and based on the independent excitation of the rotating cloud by the valence quarks. It would lead therefore to the negative binomial form of the multiplicity distribution

$$P_n = \frac{\Gamma(n+k)}{\Gamma(n+1)\Gamma(k)} \left(\frac{\bar{n}}{\bar{n}+k}\right)^n \left(\frac{k}{\bar{n}+k}\right)^k,$$

(17)

where parameter $k = \langle N \rangle$, i.e. it should be interpreted as the averaged over impact parameter number of the active valence quarks (quarks which excite the cloud) at the given high energy:

$$\langle N \rangle = \frac{\int_0^\infty b db N(b) \eta(s, b)}{\int_0^\infty b db \eta(s, b)},$$

(18)

where $N(b)$ is the distribution of the quark number over impact parameter and

$$\eta(s, b) = \frac{1}{4\pi} \frac{d\sigma_{inel}}{db^2}$$
is the inelastic overlap function. Since we adopted hadron structure with the valence constituent quarks in the central part, the function \( N(b = 0) = N \), where \( N = n_{h_1} + n_{h_2} \) is the total number of the valence quarks in the colliding hadrons. Eq. (18) implies that the probability of inelastic interaction of valence quark is proportional to the probability of the hadron inelastic interaction. The form (17) for the multiplicity distribution is in a good agreement with experimental data, e.g. at CERN SPS energy, where parameter \( k \) varies in the region from 4.6 to 3.2 [15]. The parameter \( k \) is decreasing with energy.

It would be useful to assess other effects of the proposed mechanism, where rotation of cloud of the virtual massive quarks appears as a main point. Due to this rotation the density of massive quarks will be different in the different parts of the cloud, it will be smaller in the central part and bigger at the peripheral part of cloud due to the centrifugal effect. At the same time the quarks in the peripheral part have a maximal transverse momenta and therefore we should observe correlation of the multiplicity and transverse momentum. Indeed, in the assumed mechanism of particle production with large transverse momenta (\( p_\perp \geq 1 \text{ GeV/c} \)) the interaction region of valence constituent quark with the cloud is determined by the geometrical radius of the quark \( r_Q \) and therefore the mean associated multiplicity at fixed impact parameter \( \bar{n}(s, b, p_\perp) \) should increase with \( p_\perp \) and depend on the azimuthal angle between vectors \( b \) and \( p_\perp \). It should be noted that

\[
\bar{n}(s, b, p_\perp) = \frac{\sum_{n\geq3} n \int dy I_n(s, b, y, p_\perp)}{\sum_{n\geq3} \int dy I_n(s, b, y, p_\perp)}
\]  

(19)

and, contrary to the flows, does not affected by the unitarity correction.

Assuming the linear dependence of the quark density on the distance from the cloud center and that all parts of the rotating cloud have the same angular velocity \( \omega \), we will then obtain simple linear dependence of the mean associated multiplicity

\[
\bar{n}(p_\perp) \simeq d(r_z) V_{r_Q} \simeq a + bp_\perp,
\]  

(20)

where \( d(p_\perp) \) is the density dependence on \( r_z = p_\perp / \omega \), where \( r_z \) is the distance from the center of the cloud. Parameters \( a \) and \( b \) depend on the energy and impact parameter and the parameter \( a \) should be interpreted as a quark density at the center of the constituent quark cloud. Such linear dependence can be in fact an oversimplification, however increase of the associated multiplicity with transverse momentum seems to be a direct consequence of the assumed constituent quark cloud rotation. It should be noted that the \( p_\perp \) and \( n \) correlations were considered as a signal for the deconfinement transition of hadronic matter long time ago by Van Hove [34]. Here we consider how the rotation effects affect such correlations. It would be interesting to perform measurements of the associated multiplicity de-
dependence on transverse momentum and its azimuthal dependence at fixed impact parameter at RHIC and the LHC.

**Discussion and conclusion**

We discussed here the nature transient state in hadronic collisions. We believe that the same state of matter has been revealed at RHIC in nuclei collisions. We were concentrated on the hadron interactions, however, we believe that the main features remain valid and for nucleus interactions also, i.e. the nature of transient state as a coherent system of strongly interacting massive quarks is the same, its rotation as a result of the angular momentum conservation and strong interaction, collective effects of this rotation for the particle production are the same too. The mechanism of particle production in the nuclei collisions can be different, in particular the discussed unitarity effects would not play a role in the case of nuclei collisions, however the role of the valence constituent quarks with a finite size\(^4\) as the objects exciting the rotating cloud of the other massive quarks seems to remain significant. The qualitative dependence of elliptic flow for hadron collisions is in agreement with the relevant experimental data for nuclei collisions: increase with \(p_\perp\) at small transverse momenta, weak dependence on \(p_\perp\) in the intermediate region and decreasing behavior with levelling off at high transverse momenta. The new PHENIX experimental data \(^{37}\) are in agreement with this qualitative picture. It should be noted that the rotation effects compensate effects of absorption and therefore the nuclear modification factor \(R_{AA}\) should have a nontrivial azimuthal dependence decreasing with \(\phi\). Since the correlations are maximal in the rotation plane, a similar dependence should be observed in the azimuthal dependence of the two-particle correlation function. Effect of rotation should be maximal for the peripheral collisions and therefore the dependence on \(\phi\) should be most steep at large values of impact parameter. We would also like to stress that linear increase with energy of the elliptic flow in the preasymptotic energy range is due to increasing density of quarks proportional to \(\sqrt{s}\) in the transient state which also is a reason for high parton opacity at RHIC. It would be interesting to perform studies of transient matter at the LHC not only in heavy ion collisions but also in \(pp\)–collisions and find possible existence or absence of the rotation effects. Such effects should be absent if the genuine quark-gluon plasma (gas of free quarks and gluons) would be formed at the LHC energies.

\(^4\)We would like to speculate at this point and to mention the possibility that the same reason, namely the geometric size of constituent quark, can lead to the appearance of the scale \((k_\perp^2) \simeq 1 (GeV/c)^2\) in heavy quark production (cf. e.g. \(^{35}\)).
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