Ion-Induced Quark-Gluon Implosion

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We investigate nuclear fragmentation in the central proton-nucleus and nucleus-nucleus collisions at the energies of CERN LHC. Within the semiclassical approximation we argue that because of the fast increase with energy of the cross sections of soft and hard interactions each nucleon is stripped in the average process off "soft" partons and fragments into a collection of leading quarks and gluons with large p_t. Valence quarks and gluons are streaming in the opposite directions when viewed in the c.m. of the produced system. The resulting pattern of the fragmentation of the colliding nuclei leads to an implosion of the quark and gluon constituents of the nuclei. The nonequilibrium state produced at the initial stage in the nucleus fragmentation region is estimated to have densities ≥ 50 GeV/fm^3 at the LHC energies and probably ≥ 10 GeV/fm^3 at BNL RHIC.

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One of the challenging theoretical phenomena is that perturbative QCD (PQCD) interactions become strong at sufficiently small x due to the fast increase with the energy of gluon densities. A number of models were suggested for the theoretical description of this new QCD regime; see, e.g., [1–3] for reviews. A common feature of all these models is that in the case of proton scattering off heavy nuclei with large radius R_A, the high-energy cross section for the most important quark-gluon configurations in the projectile nucleon reaches the black-body limit (BBL) $\sigma_{\rm tot} = 2\pi R_A^2$ [4]. They have this feature because, for the majority of the quark-gluon components of the nucleon wave function, the interaction cross section satisfies the condition: $\sigma 2\rho R_A \gg 1$. Therefore, most components are absorbed by the nuclear target. Here $\rho \approx 0.16$ fm^{-3} is the nuclear density. For the central nucleus-nucleus collisions, the cross section of hard interaction is even more enhanced by the factor $[g_A(x, Q^2)/\pi R_A^2]/(g_N/\pi r_N^2) \approx A^{1/3}(g_A/Ag_N) \approx 6$ for $A \approx 200$. Part of the enhancement disappears because of the leading twist nuclear shadowing phenomenon. Evidently, the soft QCD interactions in the nucleon-heavy nucleus collisions at the CERN Large Hadron Collider (LHC) should also be close to the BBL because of $\sigma_{\rm tot}(pp) \approx 100$ mb.

The numerical estimates indicate that already for $x \sim 10^{-4}$ the perturbative cross section of the interaction of $q\bar{q}$ dipoles of transverse sizes $d \geq 0.15$ fm with nuclei calculated within the framework of the QCD factorization theorem reaches BBL while for the octet dipoles of similar sizes this regime may start at x about 10 times larger. For the recent numerical studies see [8]. Hence, the proton (ion)–heavy ion collisions at LHC will be qualitatively different from those at fixed target energies and as well as at the BNL Relativistic Heavy Ion Collider (RHIC) where typical $x \geq 10^{-2}$ for the central rapidities. This should lead to a number of novel soft and hard phenomena [9,10].

Here we will argue that in this new regime, at the initial stage of the heavy ion collisions, a very dense nonequilibrium quark-gluon state will be formed in the nucleus fragmentation region. Before addressing the case of heavy ion collisions, we briefly discuss the case of the central pA collisions. To visualize the space time picture of the BBL in the proton-nucleus collisions, let us consider the rest frame of the nucleus. Within the semiclassical approximation valence partons keep the momentum of energetic parent projectiles. This property of the infinite momentum frame Schrödinger wave function in the initial and intermediate states is well known in the nonrelativistic quantum mechanics, in the PQCD approximations, in the parton model approach. It is valid also in BBL where a new strong interaction is important for the large intervals in rapidity only. But because of dominance in this case of the kind of two body kinematics such interaction does not change the fraction of projectile momentum carried by the valence partons. At the same time the distribution of small x bare particles is far from understood because the operator of the number of bare particles is not the integral of motion in QCD. So, the spectrum of leading hadrons, the probability of the gap in rapidity between projectile, and the target fragmentation may depend on the atomic number. The semiclassical approximation agrees well with the conventional picture of high-energy hadron-hadron collisions. Fast partons in a nucleon with momentum p_N are contracted to a pancake of transverse radius r_N and a small longitudinal size $z = r_N m_N/p_N$, while the small x partons form a pancake of x_V/x times larger longitudinal size ($x_V \approx 0.2$ is the average x of the valence quarks). The strong interaction of a nucleon with a target occurs when the longitudinal size of the fast nucleon becomes comparable with the nucleon radius. It is small x partons of longitudinal size $\sim$1 fm which eventually interact with the target. Thus valence quarks and gluons of the projectile keep practically the same longitudinal momentum during collision. It is the distribution of small x partons which is influenced by the nucleus medium. This phenomenon is the essence of the parton model, and of the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) evolution of hard processes and current models for the energy losses [11]. In the next discussion, we will use this property of QCD.

A parton with sufficiently large x belonging to the proton emits a virtual photon (hard gluon) long before the target and it interacts with the target, in a black regime releasing the fluctuation, e.g., a Drell-Yan pair. This leads to a qualitative change in the interactions for the partons with x_p, p_t satisfying the condition that

$$x_A = 4p_t^2/(x_p s_{NN}) \tag{1}$$

is in the blackbody kinematics for the resolution scale $p_t \leq p_t^{b.b.l.}(x_A)$. Here, $p_t^{b.b.l.}(x_A)$ is the maximum p_t for which the blackbody approximation is applicable. In the kinematics of LHC, $Q^2 \approx 4(p_t^{b.b.l.})^2$ can be estimated by using formulas derived in [12]. At minimal x_A, $p_t^{b.b.l.}$ may reach 4 GeV$/c$. All the partons with such x_p will obtain $p_t(\text{jet}) \sim p_t^{b.b.l.}(x_A)$ leading to the multijet production. The blackbody regime will extend down in x_p with increasing the incident energy. For LHC, for $p_t \leq 3$ GeV$/c$, this regime may cover the whole region of $x_p \geq 0.01$ where of the order of 10 partons reside. Hence, in this limit most of the final states will correspond to multiparton collisions. For $p_t \leq 2$ GeV$/c$ the region extends to $x_p \geq 0.001$. At LHC collisions of such partons result in the generation of partons at central rapidities. The dynamics of conversion of the high p_t partons with similar rapidities to hadrons is certainly a collective effect which deserves special consideration.

The total inclusive cross sections in pA scattering can be calculated within BBL using a similar method to that used in γ^*-nucleus scattering [13]. In particular, the total cross section of the dimuon production is

$$\frac{d\sigma(p + A \to \mu^+\mu^- + X)}{dx_A dx_p} = \frac{4\pi\alpha^2}{9}\frac{K(x_A, x_p, M^2)}{M^2} F_{2p}(x_p, Q^2) \cdot \frac{1}{6\pi^2} M^2 \cdot 2\pi R_A^2 \ln(x_0/x_A). \tag{2}$$

Here the K factor has the same meaning as in the leading twist case, but $K - 1$ should be smaller since it originates from the gluon emissions from the parton belonging to the proton only. x_0 is the maximal x for which BBL is valid. For the smallest x_A (forward kinematics) Eq. (2) may be valid at LHC for $M^2 \leq 60$ GeV^2. Obviously, the Eq. (2) prediction for the M^2, x_A dependence of the cross section is distinctively different from the DGLAP limit. This difference would be less pronounced in the case of pp scattering where scattering at large impact parameters may mask the BBL contribution. Another signal for the onset of the BBL is a broadening of the p_t distribution of the dimuons as compared to the DGLAP expectations; see [14] for a calculation of this effect in the color glass condensate model. This effect is similar to the case of p_t distribution of leading partons in the deep inelastic scattering [12].

As x_A decreases further, the formulas for BBL will probably overestimate the cross section because the interaction with a heavy nucleus of sea quarks and gluons in the projectile proton would become black as well.

The onset of the BBL will lead also to gross changes in the hadron production: there is a much stronger drop with x_F of the spectrum in the proton fragmentation region accompanied by a significant p_t broadening of the spectrum. There is also the enhancement of hadron production, at smaller rapidities. Indeed, the individual partons in this limit are resolved at the virtuality scale corresponding to transverse momenta $\sim p_t^{b.b.l.}$ without losing a finite fraction of the light-cone momentum. Hence, the limit of independent parton fragmentation [15] will be realized with an important amplification since the leading partons will have much larger transverse momenta [16] than that expected from the estimate of [15] based on the p_t broadening observed at the fixed target energies. We want to emphasize here that the approximation of zero fractional losses holds in the PQCD regime and appears to hold in the various models of the onset of the BBL; see, e.g., [16]. At RHIC this regime may hold for the very forward hadrons and could be checked [17] by studying the production of leading hadrons in the central $p(^2H)A$ collisions [18]. The propagation of a proton interacting in the BBL results in the removal of all partons in the nucleus with the proton impact parameter and $p_t \leq p_t^{b.b.l.}$. This leads to the formation of a $\sim$1 fm radius tube in a perturbative phase. Thus, the essence of the BBL is the striping of nucleons off the soft QCD modes and releasing the gas of free quarks and gluons with large transverse momenta. Remember that the PQCD interactions between quarks and gluons within the same fragmentation region are small. Thus, we conclude that the effects of the BBL should be first manifested in the projectile fragmentation region and should gradually expand towards central rapidities. The detectors with a forward acceptance would be optimal for this physics.

Let us now discuss the nucleus fragmentation region in the central heavy ion collisions. It was discussed previously in the framework of the soft dynamics, see [19] and references therein, and a significant increase of the densities was found. Let us demonstrate now that even more striking effects are expected in the BBL regime. In this case (in difference from pA collisions) soft modes will be stripped off in the whole volume of the nucleus. To calculate the properties of the quark-gluon state produced in the tube of radius R_A in the target fragmentation region we first evaluate the main characteristics of the process in the rest frame of the fragmenting ion. The incoming nucleus is a pancake shape with the longitudinal length ~ 1 fm for the soft interactions and the longitudinal length $r_N(m_N/p_N)(x_V/x)$ for hard interactions. Hence, the nucleons at different locations along the collision axis are hit one after another. In the BBL no spectators are left. The hit partons are produced with the same x that they had in the nucleus (since the energy losses are $\propto 1/s$). We also have average $p_t \sim p_t^{b.b.l.}$ and virtuality $\mu^2 \leq (p_t^{b.b.l.})^2$. The partons move in the direction of the projectile nucleus. Since they are emitted at finite angles their longitudinal velocity is smaller than the speed of light. Hence, they are left behind the projectile wave. However, since the emission angles are small the shock wave is formed compressing the produced system in the nucleus rest frame; see discussion below.

To estimate the produced densities, we first calculate the emission angles. Since the parton's x is not changed,

$$(E_i - p_i^z) = x m_N, \tag{3}$$

leading to

$$p_z = (\mu^2 + p_t^2)/2xm_N - xm_N/2 \approx p_t^2/2xm_N. \tag{4}$$

Here in the last equation we have neglected μ^2 compared to p_t^2 which is legitimate in the leading order. Since $\mu^2 \geq 0$, neglected terms would increase p_z making the emission angles, θ, even smaller. Thus in the BBL the angles θ,

$$\theta = p_t/p_z \sim 2xm_N/p_t, \tag{5}$$

are small. So the length of the produced wave package is reduced from a naive value of 2 R_A by a large factor

$$S = 1/(1 - \cos\theta) \approx p_t^2/2x^2m_N^2. \tag{6}$$

However, we must also take into account that the products of the nucleon fragmentation as a whole move forward in the target rest frame. The four-momentum of the system can be calculated from the condition that this parton system carries almost all of the light-cone momentum of the initial nucleon:

$$(\sqrt{M^2 + p_z^2} - p_z)/m_N = 1, \tag{7}$$

where $M^2 = \sum_i p_{i,t}^2/x_i$ is the square of the invariant mass of the system. Hence, $p_z = M^2/2m_N$, and the Lorentz factor

$$\gamma = E/M = \sqrt{M^2 + (M^2/2m_N)^2}/M \approx M/2m_N. \tag{8}$$

Combining Eqs. (6) and (8) we find for the decrease of volume relative to the nucleus volume:

$$D = (2m_N/M)\langle p_t^2/2m_N^2x^2\rangle. \tag{9}$$

First, to make simple numerical estimates we assume that all relevant partons carry equal light-cone fractions $1/N$. (Actually, an account of the dispersion in x_i leads for a further decrease of the volume and hence to a larger density of the produced system; see below.) In this case we obtain

$$D = M/m_N = Np_t/m_N. \tag{10}$$

Thus, we have demonstrated that the volume is indeed significantly smaller than the nuclear volume.

The next step is to estimate the energy per unit volume, R_E. It is convenient to present it in units of the energy density of nuclear matter which equals 0.16 GeV/fm^3. The lower limit on R_E is obtained by neglecting the dispersion in x_i and taking $x_i = 1/N$,

$$R_E = D \cdot Np_t/m_N = N^2p_t^2/m_N^2. \tag{11}$$

At LHC for $x \geq 0.01$ the BBL extends up to $p_t =$ 2–3 GeV$/c$, and the number of partons for such x and virtualities is $\sim$8–10. This leads to

$$R_E > 250. \tag{12}$$

If we take into account the dispersion in x_i we find

$$R_E = \sum_i p_{it}^2/m_N^2x_i^2. \tag{13}$$

Though in the first approximation the dispersion can be neglected for valence quarks and probably for the gluons separately, the quarks carry an average x that is significantly larger (a factor of 2) than gluons. This leads to a further increase in the energy density. Taking $N_q = 3$, $x_q = 1/6$, $N_g = 6$, and $x_g = 1/12$, we find a rather modest increase of R_E (a factor of 4/3) for the same $N = 9$, corresponding to the energy densities ≥ 50 GeV/fm^3. (If we assume proximity of BBL at RHIC for the fragmentation region for $p_t \sim 1$ GeV$/c$, we find quark-gluon energy densities $\sim$10 GeV/fm^3 [20].) More significantly, the difference in average x's of quarks and gluons leads to a different direction of the flow of the quarks and gluons in the c.m. frame of the produced system. For the above numerical example, $k_3/k_t \sim 0.6$ for quarks and ~ -0.3 for gluons. Obviously, this pattern will enhance the interactions of quarks and gluons at the next stage of the interactions, making equilibration more likely.

Let us briefly discuss these interactions and the possible experimental signals. It follows from Eqs. (9)–(13) that at the LHC in the first stage of collisions a strongly compressed hot quark-gluon state of the ellipsoidal shape is formed with the small principal axis of $\sim$1 fm and density $\rho \geq 25$ partons per fm^3. At the higher rapidity end, this ellipsoid boarders essentially parton free space; on the end close to central rapidities, it boarders a hot $q\bar{q}g$ state. The scattering length for parton i can be estimated as $l_i = 1/(\sum_j N_j\sigma_{ij})$, corresponding to the scattering length being smaller than 1 fm for $\sigma \geq 0.5$ mb. To estimate the interaction cross section, we note that the average invariant energy $s \approx 2p_t^2 \sim 8$ GeV^2. The initial stage of reinteractions certainly is a highly nonequilibrium process. Nevertheless to do a perturbative estimate we can conservatively introduce a cutoff on the momentum transfer $p \sim \frac{\pi}{2}\rho^{-1/3}$, leading to the leading order estimate for the gluon-gluon cross section ≥ 1 mb. Nonperturbative effects, which remain strong in the gluon sector up to $\sqrt{s} \sim 3$ GeV, are likely to increase these interactions further. Consequently, we expect partons to rescatter strongly at the second stage, though much more detailed modeling is required to find out whether the system may reach thermal equilibrium. The large angle rescatterings of partons will lead to production of partons at higher rapidities and repopulation of the cool region. In particular, two gluons have the right energies to produce near threshold $c\bar{c}$ pairs and in particular χ_c mesons with rather small transverse momenta and $x_F(c\bar{c}) \sim 2x_g \sim 0.1$. Also leading photons can be produced in the $qg \rightarrow \gamma q$ subprocesses, though in difference from the central region the $q\bar{q} \rightarrow \mu^+\mu^-$ production will be suppressed due to the lack of antiquarks. Another high density effect is the production of leading nucleons via the recombination of quarks with subsequent escape to the cool region. Hence we expect a rather paradoxical situation that the production of leading hadrons in AA collisions will be stronger than in the central pA collisions.

To summarize, we have demonstrated that the onset of the blackbody regime in the interactions in the target fragmentation region which is likely at LHC for a large range of virtualities, will lead to the formation of a new superdense initial state in the nuclei fragmentation region with densities exceeding nuclear densities at least by a factor of 300. Our reasoning is however insufficient to demonstrate whether thermalization processes will be strong enough for the system to reach equilibrium necessary for the formation of metastable states — new QCD phases suggested in a number of recent papers; see the review in [21].

Further studies of the experimental manifestations of the formation of high density quark-gluon states are needed as well as an investigation of hard processes in the central proton-nucleus collisions which will allow a determination of whether this new state of valence quark-gluon matter can be formed at current RHIC energies. Similar effects, like correlation of high p_t hadron production in the fragmentation regions, should be present in the central pp collisions at LHC (where jet production at central rapidities is used as a trigger of centrality [9]).

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