The collective effect of emission by the forward moving partons of high energy Cherenkov gluons in nucleus-nucleus collisions at RHIC and LHC energies is considered. It can reveal itself as peaks in the pseudorapidity distribution of jets at midrapidities or as a ring-like structure of individual events in event-by-event analysis. The pseudorapidity distribution of centers of dense isolated groups of particles in HIJING model is determined. It can be considered as the background for Cherenkov gluons. If peaks above this background were found in experiment, they would indicate new collective effects.

The search for collective effects in hadronic and nuclear high-energy reactions has always been one of the mainstreams of experimental and theoretical investigations. Among them, Cherenkov gluons [1, 2] and Mach waves [3] were discussed long ago. Cherenkov gluons are the intuitive analogue to Cherenkov photons if the electron beam is replaced by the bunch of partons (quarks and gluons) traversing the nuclear medium. In their turn, Mach waves could appear in this medium if the parton (jet) speed exceeds the speed of sound. Recently, the interest to these effects was revived [4, 5, 6, 7, 8, 9] in connection with RHIC data [10] as reviewed in [4]. The common feature of these collective coherent processes is particle production concentrated on a cone with the polar angle $\theta$ defined by the condition

$$\cos \theta = \frac{c_w}{v},$$

if the infinite medium at rest is considered and the direction of the parton motion is chosen as the cone axis. Here $v$ is the velocity of the parton producing these effects, $c_w$ is the phase velocity of gluons, or sound velocity in the medium.
The main experimental signature of both effects would be two peaks in the pseudorapidity distribution of particles produced in high energy nuclear collisions which are positioned in accordance with Eq. (1). The most visual image of these effects is the ring-like structure of events in the plane perpendicular to the direction of propagation of the body initiating them.

At high energies of initial partons (jets) $v \approx c$. The velocity $c_w$ can range from quite low values to a value slightly below $c$ according to present estimates for both effects (see [4]). The lowest values of $c_w$ are obtained for rarefied media and low energy gluons, while larger $c_w$ correspond to strong shock waves and high energy gluons.

For gluons, $c_w = c/n$ where $n$ is their nuclear index of refraction in a nuclear matter through which they move. The necessary condition for this effect is that the real part of the index of refraction be larger than 1. This index was estimated from experimental data on hadronic reactions [2, 4] with assumption that gluons as carriers of strong forces should possess the features common to hadronic reactions. Its value is proportional to the real part of the forward scattering amplitude, and we know from experiment (and from its Breit-Wigner and dispersion relations theoretical description) that for any hadronic process it becomes positive in presence of any resonance and at very high energies. Thus, the necessary condition is satisfied in these cases and one can wait for observable effects with low energy and high energy gluons.

For low energy gluons which can generate hadronic resonances, the real part of the nuclear index of refraction can be written [4] as

\[ \text{Re} n^r = 1 + \Delta n^r_R = 1 + \frac{3m_\pi^3}{2\omega_r^2 \Gamma}. \]  

Here $\omega_r$ is the energy required to produce a resonance. It can be of the order of the pion mass $m_\pi$. Since the widths of known resonances $\Gamma$ are of the order of hundred MeV, $\Delta n^r_R$ can be of the order of 1. Therefore, according to (1), the angle of particles emission is rather large in the target rest system. The effect can be observed at RHIC and LHC if initial partons (jets) move at a large angle with respect to the collision axis. In such a way one can try to interpret the recently observed at RHIC [10] effect with two peaks in angular distribution about the direction of propagation of the companion jet created in the direction perpendicular to the collision axis. The peak position showed that $c_w = 0.33c$. Thus, it could be the emission of low energy Cherenkov gluons with nuclear index of refraction equal to 3. In this case the resonance production should be enlarged in this angular region. It can result in different ratio of pions to protons compared to that outside this region. In
it was interpreted as Mach waves with $c_w = 0.33c$. However, the special trigger is needed to observe this effect as it was done in [10]. Moreover, the production of the trigger and companion jets at $90^\circ$ is rather rare process which requires the high statistics experiment. This effect is unobservable at RHIC and LHC for the forward moving partons because in this case the large emission angles in the target rest system are transformed to angles extremely close to $\pi$ in RHIC and LHC systems. However, it could be observable for forward moving partons in fixed target experiments as peaks at about $70^\circ$ but, strangely enough, no such observations have yet been presented.

The impinging nuclei can be considered as bunches of the forward/backward moving high energy partons passing through each other. Beside unobservable at RHIC and LHC (as explained above) low energy gluons, each initial forward moving parton can emit high energy Cherenkov gluons when traversing the target nucleus (as well as target partons can do the same in the opposite hemisphere). The real part of the nuclear index of refraction has been estimated [2] using the formula

$$
\text{Re}n^h_R(\omega) = 1 + \Delta n^h_R(\omega) = 1 + \frac{3m^3_\pi}{8\pi\sigma(\omega)}\rho(\omega),
$$

where $\rho(\omega) = \text{Re}F/\text{Im}F$, $F(\omega)$ and $\sigma(\omega)$ being the hadronic forward scattering amplitude and the cross section. It becomes positive above some threshold, increases and then decreases at high energies $\omega$ so that

$$
\Delta n^h_R(\omega) \approx \frac{a}{\omega},
$$

where $a \approx 2 \cdot 10^{-3}$ GeV if $\rho \approx 0.1$ as it follows from experiment, and assumed to remain constant at higher energies. The index $h$ refers to high energy gluons. Therefore, according to (1), the angle of particles emission is quite small in the target rest system but much larger than bremsstrahlung angles. If transformed to RHIC or LHC systems, these angles can become large (somewhere in the midrapidity region). The effect can be observed if initial it partons (jets) move (almost) along the collision axis. There are numerous experimental indications in favor of this effect (see review in [4]). The first one of them was presented in [11]. Most results are, however, either for individual cosmic rays events or for special samples of events at accelerator energies.

Here we should mention that the finite length of nuclear targets can change somewhat the estimate (1): enlarge the transverse momenta of particles in Cherenkov jets and influence the difference between processes with different colliding nuclei [2, 4].
In what follows we discuss high energy Cherenkov gluons at RHIC and LHC energies produced by forward moving partons. The important problem of experimental search for this effect is the shape of the background due to “ordinary” processes. Its influence should be minimized. For doing this we propose to use the distinctive feature of production of high energy Cherenkov gluons. Namely, such gluon should produce a jet of particles which can be distinguished as a high density isolated group of particles. Therefore, the distributions of groups (jets) of particles should be considered rather than inclusive particle distributions. Separating such groups from experimental data one would increase the relative contribution of jets produced by Cherenkov gluons. By such selection we exclude weakly correlated particles. Statistical fluctuations and hard QCD-jets are still accounted for but their relative probability is reduced and pseudorapidity distribution must be rather smooth. Therefore the role of background in the distribution of the centers of such groups becomes lower compared to the overall pseudorapidity distribution. Peaks corresponding to Cherenkov gluons should be more pronounced.

To estimate the background we have used the HIJING model for central collisions ($b = 0$) for Au–Au collisions at RHIC energy $\sqrt{s} = 200A$ GeV and for Pb–Pb collisions at LHC energy $\sqrt{s} = 5500A$ GeV. 3500 events were generated in each case. We have chosen the central collisions because the number of forward moving participants and, correspondingly, their role is larger in central collisions of heavy nuclei. Moreover, the Cherenkov radiation intensity is proportional to the length of the parton path in the medium. It is also larger in central collisions.

Then the peaks in individual HIJING events exceeding the regular distribution by more than one and two standard deviations have been separated. They can appear either as purely statistical fluctuations or as hard QCD-jets. Figs 1a and 2a show the examples of such events (for RHIC and LHC energies, correspondingly) plotted over the smooth inclusive pseudorapidity distributions.

Peaks exceeding the distributions are clearly seen. All simulated events have been plotted in such a way and centers of peaks defined. Finally, the distribution of the centers of these peaks was plotted. Figs 1b and 2b show these distributions for peaks exceeding the inclusive background at RHIC and LHC energies by two or one standard deviations. It is seen that these distributions are flat with extremely small irregularities. This agrees with our expectations that statistical fluctuations and QCD jets do not have any preferred emission angle and should be randomly dispersed over the inclusive
particle distribution. They can be considered as a background for experimental search for Cherenkov gluons which do have such preferred angle. High energy Cherenkov jets should have quite narrow angular spread. If their angular width corresponds to a single bin in Figs. 1 and 2, then they would produce peaks twice exceeding this background even when their cross section is only 5 per cent of the cross section in the considered interval of pseudorapidities. If experimental data on group centers distribution show some peaks at definite pseudorapidity values over this background, this can be indicative of new collective effect, not considered in HIJING. These findings may be added to the experimental evidence in favor of such effect collected before (they are reviewed in [4]).

It is easy to check from Figs that the levels of the background for $1\sigma$ and $2\sigma$ fluctuations correspond to the traditional statistical estimates of about 30% and 5%. However, in principle, these levels could be counted, e.g., from the inclusive pseudorapidity distribution, so the background would have certain distinct shape. It should be stressed once again that the main result of the paper consists in the constancy of this background. The presence of the traditional QCD jets in HIJING does not change it. This simplifies experimental task of search for deviations from the flat distribution.

To conclude, the pseudorapidity distributions of the centers of dense isolated groups of particles (jets) exceeding in individual events the inclusive distribution are plotted for events generated according to HIJING model at RHIC and LHC energies. They are very flat and provide the background for further searches for such collective effects as Cherenkov gluons and Mach waves. If the peaks in the pseudorapidity plot of the centers of separated groups are found in experiment and fit the condition (1), then it will testify in favor of a Cherenkov gluons hypothesis. The positions of the peaks reveal such property of hadronic matter as its nuclear index of refraction and can be valuable for understanding the equation of state of the nuclear medium.

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Figure 1: (a) The pseudorapidity distribution in one of HIJING events (dashed histogram) for central Au–Au collision at $\sqrt{s}=200A$ GeV is plotted over the inclusive HIJING distribution (solid histogram), $N_{\text{particles}}$ — number of particles. Peaks above the inclusive plot are clearly seen. (b) The pseudorapidity distribution of the centers of dense isolated groups of particles similar to those shown in Fig. 1a and exceeding the inclusive plot by two and one standard deviations $\sigma$, $P_{\text{jet}}$ — probability to find peak above mean $+ \sigma$ ($2\sigma$). This is the smooth background for further searches of collective effects.
Figure 2: (a) The pseudorapidity distribution in one of HIJING events (dashed histogram) for central Pb–Pb collision at $\sqrt{s}=5500A$ GeV is plotted over the inclusive HIJING distribution (solid histogram), $N_{\text{particles}}$ — number of particles. Peaks above the inclusive plot are clearly seen. (b) The pseudorapidity distribution of the centers of dense isolated groups of particles similar to those shown in Fig. 2a and exceeding the inclusive plot by two and one standard deviations $\sigma$, $P_{\text{jet}}$ — probability to find peak above mean $+\sigma$ ($2\sigma$). This is the smooth background for further searches of collective effects.
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