ČERENKOV GLUONS*

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The coherent hadron production analogous to Čerenkov radiation of photons gives rise to the ring-like events. Being projected on the ring diameter they produce the two-bump structure recently observed for the away-side jets at RHIC. The position of the peaks and their height determine such properties of the hadronic medium as its nuclear index of refraction, the parton density, the free path length and the energy loss of Čerenkov gluons. Beside comparatively low energy gluons observed at RHIC, there could be high energy gluons at LHC, related to the high energy region of positive real part of the forward scattering amplitude and possessing different characteristics.

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Analogous to Čerenkov photons, the Čerenkov gluons [1–5] can be emitted in hadronic collisions provided the nuclear index of refraction n exceeds 1. The partons moving in such nuclear medium would emit them. These gluons should be emitted at the cone surface with the cone angle θ to the momentum of the parton-emitter in the *rest system* of the *infinite* medium defined by the relation

$$\cos\theta = \frac{1}{\beta n}\,, \tag{1}$$

where β($\approx$ 1 for relativistic partons) is the ratio of the velocities of the parton and light.

Thus the ring-like two-dimensional distribution of particles must be observed in the plane perpendicular to the momentum of the parton.

Such a structure is seen in three-particle correlations at RHIC energies [6,7]. RHIC experiments [8,9] have also shown the two-bump structure of the azimuthal angle distribution (now with z-axis chosen along the collision axis)

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near the away-side jets. It results due to the one-dimensional projection of the ring on the azimuthal plane. It reminds the figures in the original papers of Čerenkov [10, 11].

From the distance between the peaks defined in angular ($\theta = D$ in PHENIX notation) variables one gets according to Eq. (1) the nuclear index of refraction. Its value is found to be quite large $n = 3$ compared to usual electromagnetic values close to 1. If interpreted in terms of the Breit–Wigner resonances, as explained below, it results in the large density of partons in the created quark–gluon system with about 20 partons within the volume of a single nucleon [14, 15]. It agrees with its estimates from v_2 and hydrodynamics. This value is also related to the energy loss of gluons estimated in [14] as $dE/dx \approx 1$ GeV/fm. The height of the peaks determines the width of the ring which in its turn defines the free path length of Čerenkov gluons [14] which happens to be long enough $R_f \sim 7$ fm. Thus they hadronize, probably, close to the surface of the initial volume.

These estimates were obtained [14] using the relation of the index of refraction to the forward scattering amplitude [16]

$$\mathrm{Re}\, n(E) = 1 + \Delta n_{\mathrm{R}} = 1 + \frac{6m_\pi^3\nu}{E^2}\mathrm{Re}\, F(E) = 1 + \frac{3m_\pi^3\nu}{4\pi E}\sigma(E)\rho(E)\,. \quad (2)$$

Here E denotes the energy, ν is the number of scatterers within a single nucleon, m_π the pion mass, $\sigma(E)$ the cross section and $\rho(E)$ the ratio of real to imaginary parts of the forward scattering amplitude $F(E)$. Thus the emission of Čerenkov gluons is possible only for processes with positive $\mathrm{Re}\, F(E)$ or $\rho(E)$. This is the necessary condition for such a process. It is well known even for ordinary matter that this general requirement is fulfilled within one of the wings of any Breit–Wigner resonance[1]. Gluons with wide energy spectrum are emitted during the collision. However, only those whose energy fits the corresponding wing of the resonance (*e.g.*, ρ-meson) which they form with the thermalized (or any other) gluons of the medium during the hadronization process can satisfy the requirement $n > 1$. Inserting the Breit–Wigner shapes in Eq. (2) one gets for a single resonance

$$\mathrm{Re}\, n(E) = 1 + \frac{2J+1}{(2s_1+1)(2s_2+1)}\frac{6m_\pi^3\Gamma_{\mathrm{R}}\nu}{EE_{\mathrm{R}}^2}\frac{E_{\mathrm{R}}-E}{(E-E_{\mathrm{R}})^2+\Gamma_{\mathrm{R}}^2/4}\,. \quad (3)$$

Here J, s_1, s_2 are spins of the resonance and its decay products, E_{R}, Γ_{R} are its position and width. The above estimates of parton density ν follow from this expression for the nuclear index of refraction with account of

[1] At the maximum of the resonance $\mathrm{Re}\, F(E) = 0$ as seen below in Eq. (3). In particular, this is used to solve the problem of abundance of elements in the Universe (*e.g.* see [17]).

all mesonic resonances (sum over R in Eq. (3)). It also predicts the unusual particle content within the ring because only $E < E_{\rm R}$ matter to get $n > 1$.

Thus the Čerenkov states formed within the ring have masses shifted to values below $m_{\rm R} - \Gamma_{\rm R}/2$ with substantial contribution of low masses. This feature is general for all resonances.

In particular, it can be noticed as an excess of low-mass lepton pairs below the ρ-meson mass. Such excess has been observed in experiment [18]. Let us stress that we do not require ρ-mesons or other resonances pre-exist in the medium but imply that they are some of the modes of its excitation formed during the hadronization process of partons. The Čerenkov gluon emission is a collective response of the quark–gluon medium to impinging partons related to its preconfinement and hadronization properties. It is defined by energy behavior of the second term in Eq. (3).

For the sake of simplicity, Eqs. (2) and (3) valid at small $\Delta n_{\rm R}$ typical for gases are used here. The value $n = 3$ corresponds to a dense liquid. Therefore, one must use [17]

$$\frac{n^2-1}{n^2+2} = \frac{m_\pi^3 \nu \alpha}{4\pi} = \sum_R \frac{2J_R+1}{(2s_1^R+1)(2s_2^R+1)} \frac{4m_\pi^3 \Gamma_R \nu}{E E_R^2} \frac{E_{\rm R}-E}{(E-E_R)^2+\Gamma_{\rm R}^2/4}, \tag{4}$$

where α denotes the colour polarizability of the colour-neutral medium. The value ν obtained from this expression is almost twice lower than given above. It does not change the qualitative conclusions about the dense medium (for more details see [14, 15]).

The Čerenkov gluons discussed above are comparatively low energy ones and coalesce to resonances. They originate from those regions of positive real part of the forward scattering amplitude which are bound within the left wings of the resonances. However, from dispersion relation predictions and experiments with various colliding hadrons we know that there exists the high energy region of hadronic reactions where the real part of the forward scattering amplitude (or $\rho(E)$) is positive for all colliding partners. It happens at energy exceeding $E_{\rm th}$=70–100 GeV in the target rest system. Considering it as a common property of hadron reactions, we hope that high energy gluons possess the similar feature as carriers of strong forces.

Thus the very high energy forward moving partons can emit high energy Čerenkov gluons producing jets.

There are no gluons with such energy at RHIC but they will become available at LHC. Namely such gluons were discussed in [1, 2] in connection with the cosmic ray event at energy 10^{16} eV (in the target rest system $E_{\rm t}$) with the ring-like structure first observed [19]. This energy just corresponds to LHC energies. The partons emitting such gluons move with high energy in the forward direction. With $\mathrm{Re}\,F(E_{\mathrm{t}})$ fitted to experimental data and dispersion relation predictions at high energies one can expect (see [1, 2]) that the excess of n over 1 behaves as

$$\Delta n_{\mathrm{R}}(E_{\mathrm{t}}) \approx \frac{a\nu_{\mathrm{h}}}{E_{\mathrm{t}}}\theta(E_{\mathrm{t}} - E_{\mathrm{th}})\,. \tag{5}$$

Here, $a \approx 2\times10^{-3}$ GeV is a parameter of $\mathrm{Re}\,F(E_{\mathrm{t}})$ obtained from experiment (with dispersion relations used) and ν_{h} is the parton density for high energy region. It can differ from ν used at low energies. $\Delta n_{\mathrm{R}}(E_{\mathrm{t}})$ decreases with energy for constant ν_{h}. In this case Eq. (2) should be applicable. It would imply that the medium reminds a gas but not a liquid for very high energy gluons, *i.e.* it becomes more transparent. However, we must stress that this behavior drastically differs from that in ordinary media where the usual refractive index approaches 1 from below at high energies. This is related to different asymptotics of total cross sections.

The angles of the cone emission in c.m.s. of LHC experiments must be very large nevertheless (first estimates in [2] are 60°–70°), *i.e.* the peaks can be seen in the pionization region at central pseudorapidities. In more detail it is discussed in [1, 2, 15, 20]. In this region the background is large, and some methods to separate the particles in the cone from the background were proposed in [20, 21].

The main difference between the trigger experiments at RHIC and this nontrigger experiment is in the treatment of the rest system of the medium. The influence of the medium motion on cone angles was considered in [22]. It is important because all the above formulas are valid for emission in the rest system of the medium.

At RHIC, the 90° trigger jet defines the direction of the away-side jet. Because of position of the trigger perpendicular to the collision axis of initial ions, the accompanying partons (particles) feel the medium at rest on the average in the c.m.s. The similar trigger experiments are possible at LHC. It is important to measure the cone angles for different angular positions of the trigger to register the medium motion.

However, in nontrigger experiments with forward moving high energy partons inside of one of the colliding ions, the rest system of the medium is the rest system of another colliding ion. Therefore the cone angle should be calculated at that system and then transformed to the c.m.s. That is why these angles are so large even at small values of the refractivity index for high energy gluons. The low energy Čerenkov gluons emitted in the target rest system are unobservable because they fly backward inside the accelerator pipe (about 180^o in c.m.s.).

Čerenkov gluons at different energies can be used to scan $(\ln 1/x - Q^2)$-plane to find different density of scattering centers. The knowledge of dispersion of the nuclear refractive index is crucial for further predictions.

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