

# Macroscopic QCD and quark-gluon plasma

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## Abstract

The high energy behavior of the quark-gluon medium described by QCD equations is considered. The parton currents traversing it induce the emission of Cherenkov gluons, the wake effect and the transition radiation. Comparison with experiment reveals quite large value of the chromopermittivity of the medium. The dispersion equations show that the proper modes of the medium develop instability.

Experimental data clearly show that the products of heavy-ion collisions can not be described as results of independent pp-collisions. The quark-gluon medium formed in the collisions of high energy nuclei, surely, possesses some collective properties (see the review paper [1]). At the classical level QCD equations are similar to those of QED. Therefore it is quite natural to use the analogy with electrodynamical processes in matter. The in-medium QCD equations differ from the in-vacuum equations by introducing a chromopermittivity ( $\epsilon$ ) of the quark-gluon medium (its collective response!).

Analogously to electrodynamics, the medium is accounted for if  $\mathbf{E}$  is replaced by  $\mathbf{D} = \epsilon\mathbf{E}$  in  $F^{\mu\nu}$ . In terms of potentials the equations of *in-medium* gluodynamics are cast in the form [2]

$$\begin{aligned} \Delta \mathbf{A}_a - \epsilon \frac{\partial^2 \mathbf{A}_a}{\partial t^2} = & -\mathbf{j}_a - gf_{abc} \left( \frac{1}{2} \text{curl}[\mathbf{A}_b, \mathbf{A}_c] + \epsilon \frac{\partial}{\partial t} (\mathbf{A}_b \Phi_c) + \frac{1}{2} [\mathbf{A}_b \text{curl} \mathbf{A}_c] - \right. \\ & \left. \epsilon \Phi_b \frac{\partial \mathbf{A}_c}{\partial t} - \epsilon \Phi_b \text{grad} \Phi_c - \frac{1}{2} gf_{cmn} [\mathbf{A}_b [\mathbf{A}_m \mathbf{A}_n]] + g\epsilon f_{cmn} \Phi_b \mathbf{A}_m \Phi_n \right), \end{aligned} \quad (1)$$

$$\begin{aligned} \Delta \Phi_a - \epsilon \frac{\partial^2 \Phi_a}{\partial t^2} = & -\frac{\rho_a}{\epsilon} + gf_{abc} (-2\mathbf{A}_c \text{grad} \Phi_b + \mathbf{A}_b \frac{\partial \mathbf{A}_c}{\partial t} - \epsilon \frac{\partial \Phi_b}{\partial t} \Phi_c) + \\ & g^2 f_{amn} f_{nlb} \mathbf{A}_m \mathbf{A}_l \Phi_b. \end{aligned} \quad (2)$$

The classical equations are obtained if all terms with explicitly shown coupling constant  $g$  are omitted, and then they remind those of QED. For the current with velocity  $\mathbf{v}$  along the  $z$ -axis:

$$\mathbf{j}(\mathbf{r}, t) = \mathbf{v}\rho(\mathbf{r}, t) = 4\pi g \mathbf{v} \delta(\mathbf{r} - \mathbf{v}t) \quad (3)$$

the classical lowest order solution of in-medium gluodynamics is [2]

$$\Phi^{(1)}(\mathbf{r}, t) = \frac{2g}{\epsilon} \frac{\theta(vt - z - r_{\perp} \sqrt{\epsilon v^2 - 1})}{\sqrt{(vt - z)^2 - r_{\perp}^2 (\epsilon v^2 - 1)}}, \quad (4)$$

and

$$\mathbf{A}^{(1)}(\mathbf{r}, t) = \epsilon \mathbf{v} \Phi^{(1)}(\mathbf{r}, t), \quad (5)$$

where the superscript (1) indicates the solutions of order  $g$ ,  $r_{\perp} = \sqrt{x^2 + y^2}$  is the cylindrical coordinate;  $z$  is the symmetry axis.

This solution describes the emission of Cherenkov gluons at the typical angle

$$\cos \theta = \frac{1}{v\sqrt{\epsilon}}. \quad (6)$$

It is constant for constant  $\epsilon > 1$ . Such effect was first observed in the cosmic ray data [3, 4, 5]. For absorbing media  $\epsilon$  acquires the imaginary part. The sharp front edge of the shock wave (4) is smoothed. The angular distribution of Cherenkov radiation widens. The  $\delta$ -function at the angle (6) is replaced by the a'la Breit-Wigner shape [6, 7] with maximum at the same angle (but  $|\epsilon|$  in place of  $\epsilon$ ) and the width proportional to the imaginary part. The ringlike distribution of particles around the (away-side) jet traversing the quark-gluon medium was observed in the form of two humps when projected on the diameter of the ring. This is completely analogous to what was done by Cherenkov in his original publications. It has been used for fits of RHIC data [7]. Both real and imaginary parts of  $\epsilon = \epsilon_1 + i\epsilon_2$  were taken into account. For two-particle correlations measured by STAR and PHENIX it was found that they are, correspondingly, about 6 and 0.8.

The real part of the chromopermittivity can be expressed through the real part of the forward scattering amplitude  $\text{Re}F_0(\omega)$  of the refracted quanta

$$\text{Re}\Delta\epsilon = \text{Re}\epsilon(\omega) - 1 = \frac{4\pi N_s \text{Re}F_0(\omega)}{\omega^2} = \frac{N_s \sigma(\omega) \rho(\omega)}{\omega} \quad (7)$$

with

$$\text{Im}F_0(\omega) = \frac{\omega}{4\pi} \sigma(\omega). \quad (8)$$

Here  $\omega$  denotes the energy,  $N_s$  is the density of scattering centers,  $\sigma(\omega)$  the cross section and  $\rho(\omega)$  the ratio of real to imaginary parts of the forward scattering amplitude  $F_0(\omega)$ . Thus the emission of Cherenkov gluons is possible only for processes with positive  $\text{Re}F_0(\omega)$  or  $\rho(\omega)$ . Hadronic experiment shows that the necessary condition for Cherenkov effects may be satisfied at least within two energy intervals - those of resonance production (left wings!) and at extremely high energies.

The first region is typical for the comparatively low energies of secondary particles registered in SPS and RHIC experiments.  $\text{Re}F_0(\omega)$  is always positive (i.e.,  $\epsilon > 1$ ) within the low-mass wings of the Breit-Wigner resonances. Therefore, Cherenkov gluons can be emitted in these energy intervals.

The asymmetry of the  $\rho$ -meson mass shape observed in leptonic decays of  $\rho$ -mesons created in nuclei collisions at SPS [8] was explained by emission of low-energy Cherenkov gluons [9, 10] inside the left (low mass) wing of the Breit-Wigner resonance. It is predicted that this feature should be common for all resonances traversing the nuclear medium. Some preliminary experimental indications which favor this conclusion have appeared for other resonances as well [9].

The experimental data of STAR and PHENIX collaborations at RHIC on two- and three-particle azimuthal correlations in central collisions discussed above also deal with rather low energies of secondary particles. Moreover, the new effect of humps shift due to wake radiation was observed in mid-central nuclear collisions [11] and explained with the same values of  $\epsilon$  [12].

In what follows, we concentrate on the extremely high energy region and study the properties of the quark-gluon medium in the model with chromopermittivity behaving above some threshold ( $\omega_{thr}$ ) as

$$\text{Re}\epsilon = 1 + \frac{\omega_0^2}{\omega^2}, \quad (9)$$

where  $\omega_0$  is some real free parameter. The classical equations derived from (1), (2) and written in the momentum space have solution if the following dispersion equation is valid

$$\det(\omega, \mathbf{k}) = |k^2 \delta_{ij} - k_i k_j - \omega^2 \epsilon_{ij}| = 0. \quad (10)$$

It is of the sixth order in momenta dimension. However, the sixth order terms cancel and (10) leads to two equations (of the second order):

$$k^2 - \omega^2 - \omega_0^2 = 0, \quad (11)$$

$$(k^2 - \omega^2 - \omega_0^2)\left(1 + \frac{\omega_0^2}{\omega^2}\right) - \frac{\omega_0^4 k_t^2}{\omega^2(\omega - k_z)^2 \gamma} = 0. \quad (12)$$

They determine the internal modes of the medium and the bunch propagation through the medium, correspondingly. The equation (11) shows that the quark-gluon medium is unstable because there exists the branch with  $\text{Im}\omega > 0$  for modes  $k^2 < \omega_0^2$ . Thus the universal energy increase of the hadronic total cross sections is directly related to the instability of the quark-gluon medium by the positiveness of  $\text{Re}F_0(\omega)$  at high energies.

The equation (12) has solutions corresponding to Cherenkov gluons emitted by the impinging bunch and determined by the last term in (12). The solutions of the dispersion equation (10) determine the Green function of the system

$$G(t, z) = \frac{1}{2\pi^2} \int_{-\infty}^{\infty} dk \int_{C(\omega)} \frac{1}{\det(\omega, \mathbf{k})} \exp(-i\omega t + ikz) d\omega, \quad (13)$$

where the contour  $C(\omega)$  passes above all singularities in the integral. Therefore, the positive  $\text{Im}\omega$  found in solutions of (12) corresponds to the absolute instability of the system. The instability exponent decreases asymptotically as  $\gamma^{-1/3}$  and is about 16 times smaller at LHC compared to RHIC.

It happens that Cherenkov gluons are emitted with constant transverse momentum  $k_t = \omega_0$  and their number is proportional to  $d\omega/(\omega)^2 \theta(\omega - \omega_{thr})$  for  $\epsilon(\omega)$  given by Eq. (9) with account of the threshold above which this equation is applicable. It differs from the traditional folklore of constant emission angle of Cherenkov radiation and the number of gluons  $\propto d\omega$  (or the total energy loss proportional to  $\omega d\omega$ ) which is correct only for constant chromopermittivity.

To conclude, the in-medium QCD equations predict the emission of Cherenkov gluons and ringlike events. The fit to experimental data of RHIC allows to find out both real (quite large!) and imaginary (relatively small!) parts of the chromopermittivity. The large real part shows the high density (large  $N_s$  in (7)) of the quark-gluon plasma while small imaginary part favors penetration of partons and, consequently, observation of the effect.

Another observed experimental effect due to Cherenkov gluons is the universal asymmetry of shapes of resonances traversing the quark-gluon medium as clearly seen from dilepton modes of their decays (at SPS and some other accelerators).

Beside Cherenkov gluons there exists the collective classical wake effect due to the trail behind the penetrating parton which has been observed in experiment as the shift of the positions of two-hump maxima in semi-central nuclei collisions at RHIC. The transition radiation of gluons may also appear.

Concerning possible new effects at LHC, one can await for Cherenkov gluons emitted by extremely high energy forward moving partons in non-trigger experiments where the values of the chromopermittivity could be very close to 1 (favored by the cosmic ray data). The dispersion law of the quark-gluon medium at high energies differs from that in the electromagnetism. Its main feature is the excess of the chromopermittivity over 1. The definite model is considered. The dispersion equation of in-medium gluodynamics shows that the quark-gluon medium is unstable and responses to external high energy partons by creation of Cherenkov gluons with specific properties.

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