Effects of macroscopic QCD observed in heavy-ion collisions

I. M. Dremin
Lebedev Physical Institute, Moscow 119991, Russia

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The solutions of macroscopic QCD equations predict the emission of Cherenkov gluons, the wake effect and the transition radiation. They take into account the collective response of the quark-gluon medium to the parton currents traversing it. 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 of RHIC 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 same time new surprises come from the LHC! It was observed that the particle densities are close to those in heavy-ion collisions at RHIC, the size of the interaction region strongly increases at high multiplicities and, moreover, the effect of narrow azimuthal correlations with large extension in pseudorapidity (ridge) appears even in pp-collisions. Probably, all that points out to the onset of new collective regimes of the quark-gluon medium also in hadronic collisions at extremely high energies. The forthcoming Pb-Pb run promises to be very exciting. I'll review the effects of the macroscopic QCD observed in heavy-ion collisions.

We study any medium by its reaction to the penetrating it probes (electrons, partons etc). The difference between micro- and macro-approaches stems from considering the matter impact on the probe in the first case and the collective matter excitations in the second. Correspondingly, the change of the velocity vector of the probe is crucial for micro-approach and results in elastic scattering, bremsstrahlung (with LPM-effect), cyclotron radiation etc. The velocity vector almost does not change in the second approach but due to the matter permittivity it results in such effects as Cherenkov radiation, wake, transition radiation. The energy loss can be considerable even here since it is related to the velocity change by the relation

$$\frac{\Delta E}{E} = (\gamma^2 - 1)\frac{\Delta v}{v} \gg \frac{\Delta v}{v} \qquad (\gamma \gg 1). \tag{1}$$

At the classical level macroscopic 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 (ϵ) 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 ($\mathbf{A}$, Φ) the equations of *in-medium* gluodynamics are cast in the form [2]

$$\triangle \mathbf{A}_a - \epsilon\frac{\partial^2 \mathbf{A}_a}{\partial t^2} = -\mathbf{j}_a - g f_{abc}(\frac{1}{2}\mathrm{curl}[\mathbf{A}_b, \mathbf{A}_c] + \epsilon\frac{\partial}{\partial t}(\mathbf{A}_b\Phi_c) + \frac{1}{2}[\mathbf{A}_b \mathrm{curl}\mathbf{A}_c] - \epsilon\Phi_b\frac{\partial \mathbf{A}_c}{\partial t} - \epsilon\Phi_b \mathrm{grad}\Phi_c - \frac{1}{2} g f_{cmn}[\mathbf{A}_b[\mathbf{A}_m\mathbf{A}_n]] + g\epsilon f_{cmn}\Phi_b\mathbf{A}_m\Phi_n), \quad (2)$$

$$\triangle \Phi_a - \epsilon\frac{\partial^2 \Phi_a}{\partial t^2} = -\frac{\rho_a}{\epsilon} + g f_{abc}(-2\mathbf{A}_c \mathrm{grad}\Phi_b + \mathbf{A}_b\frac{\partial \mathbf{A}_c}{\partial t} - \epsilon\frac{\partial \Phi_b}{\partial t}\Phi_c) + g^2 f_{amn} f_{nlb}\mathbf{A}_m\mathbf{A}_l\Phi_b. \quad (3)$$

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:

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

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

$$\Phi^{(1)}(\mathbf{r},t) = \frac{2g}{\epsilon}\frac{\theta(vt - z - r_\perp\sqrt{\epsilon v^2 - 1})}{\sqrt{(vt-z)^2 - r_\perp^2(\epsilon v^2 - 1)}}, \quad (5)$$

and

$$\mathbf{A}^{(1)}(\mathbf{r},t) = \epsilon\mathbf{v}\Phi^{(1)}(\mathbf{r},t), \quad (6)$$

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. Note that g is implicitly contained in ϵ.

Cherenkov gluons are emitted according to this solution at the typical angle

$$\cos\theta = \frac{1}{v\sqrt{\epsilon}}. \quad (7)$$

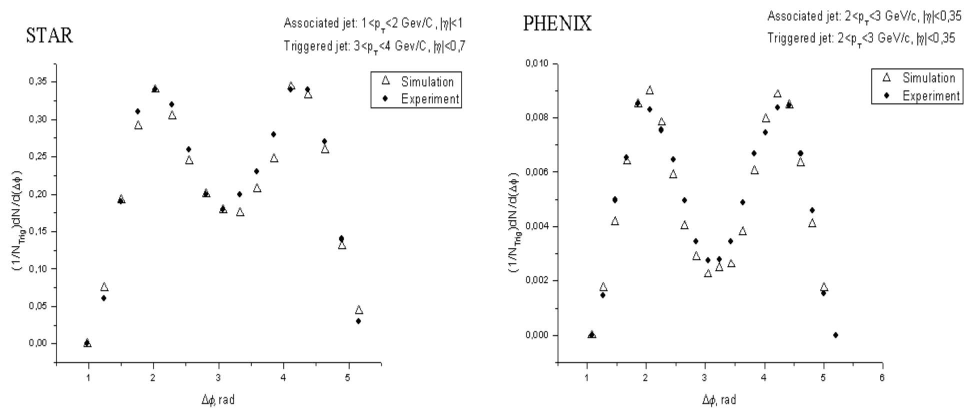
It is constant for constant $\epsilon > 1$. Such effect was first observed in the cosmic ray data [3, 4, 5]. For absorbing media ϵ acquires the imaginary part. The sharp front edge of the shock wave (5) is smoothed. The angular distribution of Cherenkov radiation widens. The δ-function at the angle (7) is replaced by the a'la Breit-Wigner shape [6, 7] with maximum at the same angle (but $\mathrm{Re}\epsilon$ in place of ϵ) and the width proportional to its imaginary part.

Similar to electrodynamics [6], one easily gets the energy-angular spectrum of emitted gluons per the unit length

$$\frac{dN^{(1)}}{d\Omega d\omega} = \frac{\alpha_S C\sqrt{x}}{2\pi^2}\left[\frac{(1-x)\Gamma_t}{(x-x_0)^2 + (\Gamma_t)^2/4} + \frac{\Gamma_l}{x}\right], \quad (8)$$

where $x = \cos^2\theta$, $x_0 = \epsilon_{1t}/|\epsilon_t|^2 v^2$, $\Gamma_j = 2\epsilon_{2j}/|\epsilon_j|^2 v^2$, $\epsilon_j = \epsilon_{1j} + i\epsilon_{2j}$. The real ($\epsilon_1$) and imaginary ($\epsilon_2$) parts of ϵ are taken into account. The angle θ is the polar angle if the away-side jet axis would be chosen as z-axis. It is clearly seen from Eq. (8) that the transverse and longitudinal parts of the chromopermittivity are responsible for the distinctly different effects. The ringlike Cherenkov structure (conical emission) around this axis is clearly exhibited in the first term of (8). The second term defined by the longitudinal part of ϵ is in charge of the wake radiation.

The ringlike distribution of particles around the away-side jet traversing the quark-gluon medium was observed at RHIC 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]. For two-particle correlations measured by STAR and PHENIX it was found that $\epsilon_1 \approx 6$ and $\epsilon_2 \approx 0.8$. The good quality of fits is demonstrated in Fig. 1. This is the very first determination of the chromopermittivity of the quark-gluon medium from experimental data. In general, it can depend on pion energies (dispersion) so that fits in other energy intervals would provide new interesting results but the accuracy of the data is not yet good enough for doing this. The collective excitations of the medium (colored resonances?) are in charge of the effect.



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

$$\mathrm{Re}\Delta\epsilon = \mathrm{Re}\epsilon(\omega) - 1 = \frac{4\pi N_s \mathrm{Re}F_0(\omega)}{\omega^2} = \frac{N_s \sigma(\omega)\rho(\omega)}{\omega} \quad (\mathrm{Im}F_0(\omega) = \frac{\omega}{4\pi}\sigma(\omega)). \tag{9}$$

Here ω 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 $\mathrm{Re}F_0(\omega)$ 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. $\mathrm{Re}F_0(\omega)$ is always positive (i.e., $\epsilon > 1$) within the low-mass wings of the Breit-Wigner resonances.

The asymmetry of the ρ-meson mass shape observed in leptonic decays of ρ-mesons created in nuclei collisions at SPS [8] was explained namely by emission of low-energy Cherenkov gluons [9, 10] inside the left (low mass) wing of **any** 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 about universality of the effect have appeared for other resonances as well [9].

The wake radiation determined by the second term in (8) explains the new effect of humps shift in mid-central nuclear collisions [11] dealing with the same values of ϵ in the same p_T-

intervals [12]. The trail behind a parton radiates somewhat similarly to a dipole and shifts the maxima.

Even more interesting can be the extremely high energy region. The recently found at CMS in pp-collisions ridge-effect indicates possible onset of collectivity in many-parton systems. At the same time it can show the general property of field-theoretical matrix elements where all particles tend to coplanarity demonstrating their (multi)peripheral nature [13].

Also, one can propose to study the properties of the quark-gluon medium in the model with chromopermittivity behaving above some threshold (ω_{thr}) as

$$\mathrm{Re}\epsilon = 1 + \frac{\omega_0^2}{\omega^2}, \tag{10}$$

where ω_0 is some real free parameter. This model is inspired by the behavior of ReF at very high energies where it becomes positive. The classical equations derived from (2), (3) and written in the momentum space have solution if the following dispersion equation is valid

$$\det(\omega, \mathbf{k}) = |k^2\delta_{ij} - k_i k_j - \omega^2\epsilon_{ij}| = 0. \tag{11}$$

It is of the sixth order in momenta dimension. However, the sixth order terms cancel and (11) leads to two equations (of the second order):

$$k^2 - \omega^2 - \omega_0^2 = 0, \tag{12}$$

$$(k^2 - \omega^2 - \omega_0^2)(1 + \frac{\omega_0^2}{\omega^2}) - \frac{\omega_0^4 k_t^2}{\omega^2(\omega - k_z)^2\gamma} = 0. \tag{13}$$

They determine the internal modes of the medium and the bunch propagation through the medium, correspondingly. The equation (12) shows that the quark-gluon medium is unstable because there exists the branch with Im$\omega > 0$ for modes $k^2 < \omega_0^2$. In such a way 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 Re$F_0(\omega)$ at high energies. In accordance with (10), at LHC the "forward" Cherenkov gluons would decline from the traditional folklore of constant emission angle and their number is $\propto d\omega$.

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 (9)) 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 seen from dilepton modes of their decays (at SPS and 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.

At the LHC, one can await for strong instabilities to appear related to new regime with chromopermittivity exceeding 1, i.e. with positive real part of forward scattering amplitudes of quark and gluon (colored?) clusters.

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