The medium in heavy-ion collisions

I.M. Dremin
Lebedev Physical Institute,
Moscow 119991, Russia
(Dated: March 26, 2022)

The nuclear index of refraction, the density of partons, their free path length and energy loss in the matter created in heavy-ion collisions at RHIC are estimated within the suggestion that the emission of Cherenkov gluons is responsible for the observed two-bump structure of the angular distribution of hadrons belonging to the companion (away-side) jet.

PACS numbers: 12.38.Mh, 25.75.Dw

Collective effects and jets are the main tools for studies of the nuclear matter created in heavy-ion collisions. The "in-vacuum" and "in-medium" jets are different. The "in-vacuum" jets have been well studied in $e^+e^-$-collisions (for reviews see, e.g., [1, 2]). Jet characteristics are, however, modified if jets traverse the nuclear medium. Jet quenching or the suppression of high $p_T$ hadron spectra is one of the well known effects induced by the dense matter. Elliptic flow and jet quenching have been widely used for analysis of partonic properties of the matter, in particular, for estimations of parton densities [3, 4, 5, 6].

A quark traversing this medium can emit gluons by the mechanism analogous to emission of Cherenkov photons in ordinary media. Thus, Cherenkov gluons [7, 8, 9, 10, 11, 12, 13] can serve as another diagnostic tool. Similarly to photons, Cherenkov gluons are emitted along the cone. Its half-angle is determined by the nuclear index of refraction $n$ as

$$\cos \theta_c = \frac{1}{n}. \quad (1)$$

Therefore, the rings of hadrons similar to usual Cherenkov rings can be observed in the plane perpendicular to the cone axis if $n > 1$.

Recent experimental observations at RHIC [14] shown in Fig. 1 revealed the two-bump structure of the angular distribution of hadrons belonging to the so-called companion (away-side) jet in central heavy-ion collisions. There is no such structure in pp-collisions. The difference has been attributed to "in-medium" effects. These features are clearly seen in Fig. 1 (the upper part for pp, lower one for Au-Au). One easily notices the remarkable difference between particle distributions in the direction opposite to the trigger jet maximum which is positioned at $\Delta \phi = 0$. Both trigger and companion high-$p_T$ jets have been created in central Au-Au collisions at $\sqrt{s} = 200$ GeV at the periphery of a nucleus. They move in opposite directions. The trigger parton immediately escapes the nucleus and, therefore, is detected as the "in-vacuum" jet. The companion (away-side) jet traverses the whole nucleus before it comes out. It is modified by "in-medium" effects. Beside normal fragmentation, its initiating parton can emit Cherenkov gluons which produce a ring of hadrons in the plane perpendicular to the jet axis.

Thus we can ascribe two contributions to the away-side hadrons associated with the companion jet: one from jet fragmentation and the other from Cherenkov gluons. The hadrons from jet fragmentation are smoothly distributed within the phase space volume. In distinction, the one-dimensional distribution along the ring diameter of the away-side hadrons created by Cherenkov gluons must possess two peaks because it is just the projection of the ring on its diameter. The distance between these peaks is exactly equal to the diameter.

In angular variables, the ring radius is given by $\theta_c$ in Eq. (1). Let us note that $\Delta \phi$ in Fig. 1 coincides with $\theta$ in our notations. Herefrom, it is determined that $\theta_c \approx 70^0$ or $(n) \approx 3$, where the average should be done over gluon energy if $n$ depends on it.

For photons, the index of refraction is usually related to their forward scattering amplitude. We use the similar relation for the nuclear index of refraction $n$ using the forward scattering amplitude $F(E)$ at energy $E$ for gluons:

$$n(E) = 1 + \frac{2 \pi N}{E} F(E). \quad (2)$$

Here $N$ is the density of the scattering centers in a nucleus. The necessary condition for emission of Cherenkov gluons is $\text{Ren}(E) > 1$ according to Eq. (1). QCD estimates of $F(E)$ are rather indefinite. Therefore, we rely on general properties of hadronic reactions known from experiment. The real part of hadronic scattering amplitudes becomes positive either within the upper wing of a Breit-Wigner resonance or at very high energies. Jet energies available in RHIC experiment [14] (Fig. 1) are sufficient only for production of resonances. Therefore, we attribute the feature shown in Fig. 1 to resonance effects as discussed in [4]. If the hadronization of gluons is a soft process then the gluon energy closely corresponds to the energy of the produced resonance. It implies that in this particular experiment [14] Cherenkov gluons can be emitted only with energies within the upper wings of hadronic resonances. Their amplitude is of the Breit-
this average value equal to 3 and Eq. (4) one gets the lower bound for the effective number of partons within the nucleon volume $\nu$

\[
\nu > \frac{(2s_1+1)(2s_2+1)}{2J+1} \cdot \frac{2E_R^3}{3\mu^3}.
\] (5)

According to Eq. (4) the factor in front of $\nu$ is mostly determined by the low-mass resonances with high statistical weights. The $\rho$-meson is a typical representative. Inserting its parameters in Eq. (4) one gets $\nu > 40$. However, in principle, the sum over all resonances should be used in Eq. (4). The largest additional items come from $\omega$ and $f_2$-mesons, each contributing about 0.3 of the $\rho$ share. With rough estimate of other meson resonances the above bound for $\nu$ becomes twice lower, i.e. about 20. The baryon contribution is negligible.

In experiment, the index of refraction is averaged in accordance with jet evolution. One can approximate this averaging procedure by the Breit-Wigner weight $\pi/(E - E_R)^2 + \Gamma_R$, multiplying the expression (4) by it and integrating over energy in the interval from $E_R$ to infinity. Then the average value of Ren is

\[
\langle \text{Ren} \rangle \approx 1 + \frac{2J + 1}{(2s_1+1)(2s_2+1)} \cdot \frac{6\mu^3}{\pi E_R^3} (6).
\]

For $\rho$-meson one gets $\langle \nu \rangle = 60$. If all mesons are taken into account the estimate would be $\langle \nu \rangle \approx 30$. This value is consistent with estimates obtained earlier from hydrodynamical interpretation of the observed collective flow [3] and jet quenching analysis [4, 5, 6]. Even if the accuracy of all these estimates is up to the factor about 2, the qualitative statement about the high density of partons stays valid. One can claim that the state of this dense matter strongly differs from a cold nuclear matter. Its scattering centers remind of some correlated current partons or their preconfined states.

According to the above discussion, one would expect that the ring regions are enriched by pions originating from $\rho$-decays. The high parton density at the initial stage somehow helps confinement provide softly the necessary partonic contents of the resonance with mass supplied by the gluon energy. The resonances in the ring region should have quite specific mass distribution only within one Breit-Wigner wing. Their average mass must be somewhat higher than the $\rho$-meson mass (about 840 MeV). It would be interesting to observe directly the ring structure of events and study their particle contents.

Another information can be obtained from the height of the peaks in Fig. 1. It determines the width of the Cherenkov ring $\delta$. This is the ring in the plane perpendicular to the cone axis filled by evenly distributed within its particles over the smooth background due to jet fragmentation. Its projection on the diameter corresponds to the particle distribution which has a minimum at the center, increases, reaches the maximum at the internal radius of the ring $r_1$ and then decreases to zero at its external radius $r_2$. For narrow rings ($\delta \ll r_1$) the height

\[
\text{FIG. 1: The } \phi \text{-distribution of particles produced by trigger and companion jets at RHIC [14] shows two peaks in } pp \text{ and three peaks in } AuAu-\text{collisions.}
\]
of the maximum over the minimum is easily determined as

$$h_{\text{max}} = \sqrt{2r_1 \delta - \delta}. \quad (7)$$

With $h_{\text{max}} \approx 1.6 - 1.2 = 0.4$ and $r_1 = 1.2$ in Fig. 1 one gets

$$\delta \approx 0.1. \quad (8)$$

The ring of Cherenkov gluons is really quite narrow. Actually, Eq. 1 implies that the ring is squeezed to a circle.

There are three physical reasons which can lead to the finite width of the ring. First, it is the dispersion, i.e. the energy dependence of the index of refraction. Its finite width of the ring. Actually, Eq. 1 implies that the ring is squeezed to a circle.

Second, the width of the Cherenkov ring can be due to the finite free path length for partons. Qualitatively, it can be estimated as the ratio of the parton wavelength $\lambda$ to the free path length $R_f$

$$\delta_f \sim \frac{\lambda}{R_f}. \quad (10)$$

For $\lambda \sim 2/E_R$ and $\delta_f < 0.1$ one gets the estimate for the free path length

$$R_f > 20/E_R \sim 4.5/\mu \sim 7 \cdot 10^{-13} \text{cm}. \quad (12)$$

This appears to be quite a reasonable estimate.

Finally, the width of the ring can become larger due to resonance decays. That is why there is the inequality sign in 12. However, this can be quantified only if the Monte Carlo program for jets with Cherenkov gluons is elaborated.

Let us note that the contribution of Cherenkov gluon emission to the away-side hadrons at the minimum in Fig. 1 is rather small, of the order of 0.1 compared to the total value at the minimum about 1.2. Jet fragmentation contributes an order of magnitude larger number of hadrons at this point.

The energy loss can be calculated using the standard formula

$$\frac{dE}{dx} = 4\pi\alpha_S \int_{E_R}^{E_R+\Gamma_R} E \left(1 - \frac{1}{n^2(E)}\right) dE \approx 1 \text{GeV/fm}. \quad (13)$$

This estimate is an order of magnitude higher than the value of 0.1 GeV/fm obtained in the model of 11 which is somewhat underestimated, in our opinion. It is so large because rather high energies are required to excite resonances. However, it is still smaller than the radiative loss.

To conclude, we have estimated such parameters of the nuclear matter in heavy-ion collisions as its nuclear index of refraction, the density of partons, their free path length and energy loss. The RHIC data on the two-bump structure of the hadron distribution in away-side jets have been used within the notion of Cherenkov gluons. In accordance with previous estimates our results show that the density of partons in high energy heavy-ion collisions is very high. This favors the hypothesis about a new state of dense matter created in heavy-ion collisions.

Acknowledgments

I thank B.M. Bolotovsky for fruitful discussions. This work has been supported in part by the RFBR grants 04-02-16445-a, 04-02-16333.