Filamentation in a quark-gluon plasma

Yu. E. Pokrovskiĭ and A. V. Selikhov
I. V. Kurchatov Institute of Atomic Energy, Moscow

(Submitted 16 November 1987)
Pis'ma Zh. Eksp. Teor. Fiz. **47**, No. 1, 11–13 (10 January 1988)

When a quark-gluon plasma is produced in a nucleus-nucleus collision, a filamentation manages to develop. This filamentation is a structural instability which can clearly be seen experimentally.

Ivanov[1] recently showed that the onset of a dynamic instability of the filamentation type should be expected in a hadronic plasma under the conditions which arise in nucleus-nucleus (AA) collisions. In general, filamentation is an instability which leads to the stratification of an initially homogeneous system of two oppositely directed fluxes which are interacting with an average vector field (in an ordinary plasma, this would be an electromagnetic field, in a hadronic plasma the field of ω mesons, and in a quark-gluon plasma a gluon field). The result of the stratification is an alternation of oppositely directed current filaments. Under the assumption that deconfinement sets in quite rapidly in AA collisions–while the nuclei are passing through each other (this assumption may be valid at sufficiently high energies)—we examine two quark fluxes in a collisionless regime on the basis of a relativistic kinetic theory with an average gluon field in the region of mutual penetration of the nuclei.[2] We derive an estimate of the time scale of the onset of the filamentation instability. This estimate indicates that filamentation can occur in a quark-gluon plasma under conditions which arise in AA collisions. A theoretical and experimental study of filamentation is of particular interest in connection with the diagnostics of quark-gluon plasmas, since (1) manifestations of filamentation are amenable to measurement under existing experimental conditions, (2) filamentation is a collective effect, which is peculiar to plasma production, (3) the observation of filamentation makes it possible to detect and study the initial stage of the production of a quark-gluon plasma, and (4) the dependence of the filamentation on the plasma temperature in each of the fluxes in principle constitutes a unique thermometer capable of measuring the initial temperature of the quark-gluon plasma.

Let us examine the solutions of the self-consistent Vlasov and Yang-Mills equations for a quark-gluon plasma. These equations describe small deviations from a thermodynamic-equilibrium state. The equilibrium distribution function is represented in color space by a unit matrix, so the expectation value of the gluon field is zero in a stationary homogeneous state. It is assumed that the perturbation $\widetilde{W}(x,p)$ of the equilibrium distribution function can be diagonalized in color space by means of a gauge transformation. The perturbations $F^a_{\mu\nu}$ of the expectation value of a gluon field with $a = 3.8$ will then be nonzero.[3] Using the standard methods,[1,3] we find a dispersion relation for small deviations

$$\det(-k^2\delta_{ij} + \Pi_{ij}(k)) = 0, \qquad (1)$$

 0021-3640/88/010012-03$01.00

where the polarization operator $\pi_{ij}(k)$ is defined in terms of the equilibrium distribution function $n(p)$;

$$\Pi_{ij}(k) = g^2/2 \int d^4p \, (p_i - \frac{p_0}{k_0} k_i) \left\{ \frac{\partial n(p)}{\partial p^i} - \frac{p_i k_\mu}{(pk)} \frac{\partial n(p)}{\partial p^\mu} \right\}.$$

Dispersion relation (1) is analogous to the dispersion relation which was derived by Ivanov[1] for a hadronic plasma by virtue of the assumption that the perturbation $\widetilde{W}(x,p)$ is of an Abelian nature. We assume that the vector **k** is directed along the z axis: $k_\mu = (\omega,0,0,q)$. We are interested in complex eigenvalues with $\mathrm{Im}\,\omega(q) > 0$, which correspond to unstable solutions that grow exponentially over time. For a quantitative estimate of the time scale for filamentation in a quark-gluon plasma, we assume that each flux has a zero temperature and is described by a distribution function

$$n(p) = (\rho/M)\,\delta^{(4)}(p - MU),$$

where ρ is the density of quarks ($\sim 0.45\ \mathrm{fm}^{-3}$), M is the quark mass, and U_μ is the 4-velocity, normalized by the condition $U_\mu U^\mu = 1$. As Ivanov showed in Ref. 1 for a hadronic plasma, the filamentation mode is most unstable in the case $\mathbf{k} \perp \mathbf{U}$. This conclusion also applies to a quark-gluon plasma. After the appropriate changes, the filamentation mode is determined by the expression

$$\omega_F^2(q) \approx -2g^2\rho/M.$$

For g^2, the effective interaction constant, we use the single-loop expression

$$g^2 = 16\pi^2/9 \ln(q^2/\Lambda^2),$$

where $\Lambda = 100$ MeV. We specify the q dependence of M phenomenologically, drawing on the results of Ref. 4:

$$M(q) = (M_0 - m_0)/(1 + (\bar{\rho} q)^6/36) + m_0, \tag{2}$$

where $M_0 = 350$ MeV, $m_0 = 5$ MeV, and $\bar{\rho} = (600\ \mathrm{MeV})^{-1}$. The values of the momentum transfer corresponding to the maximum instability of the filamentation mode lie in the interval $\sim$1–4 GeV/c. The reason for this spread is that expression (2) is good only for rough estimates at large values of q. For the rise time of the filamentation mode we find

$$\Delta t_F \sim 1/\mathrm{Im}\,\omega_F \sim 0{,}1\ \mathrm{fm/s}.$$

The quantity Δt_F should be compared with Δt_c, the time scale of an AA collision, which we assume to be roughly equal to the time taken by one nucleus to pass through the other. For heavy nuclei (with $A \sim 200$) at $E_{\mathrm{c.m.}} = 20$ GeV/nucleon we find $\Delta t_c \sim 3.6$ fm/s, while at $E_{\mathrm{c.m.}} = 50$ GeV/nucleon we find $\Delta t_c \sim 1.4$ fm/s.

These estimates in principle make it possible to use filamentation to study the question of the initial stage of deconfinement in AA collision over a broad range of A, including light nuclei. A quark-gluon plasma has a filamentation onset time which is considerably shorter (by an order of magnitude) than that of a hadronic plasma. This difference can serve to distinguish between signals from quark-gluon plasmas and hadronic plasmas. Ivanov[1] has pointed out that the most direct method for observing filamentation in a hadronic plasma is to study the γ rays with $E_\gamma \sim 200$ MeV which accompany this process. A characteristic property of the spectrum in the c.m. system is a narrow peak in the direction perpendicular to the collision axis. This is also true of quark-gluon plasmas, but in this case we would have $E_\gamma \sim 1$–4 GeV. Gluons in a quark-gluon plasma and ω mesons in a hadronic plasma would be emitted considerably more intensely than γ rays; the emission would be followed by a conversion into π mesons in either case. A distinction between quark-gluon plasmas and hadronic plasmas is seen in the circumstance that 3π correlations should not contain filamentation structures if they are emitted by a quark-gluon plasma. The filamentation approach is sensitive enough to detect the formation of hadronic and quark-gluon plasmas and to distinguish them from each other.

We wish to thank Yu. B. Ivanov for furnishing a paper before its publication.

[1]Yu. B. Ivanov, Nucl. Phys. **A474**, 693 (1987).
[2]U. Heinz, Phys. Rev. Lett. **51**, 351 (1983).
[3]St. Mrovczynski, Phys. Lett. **B188**, 129 (1987).
[4]D. I. D'yakonov and V. I. Petrov, Zh. Eksp. Teor. Fiz. **89**, 361 (1985) [Sov. Phys. JETP **62**, 204 (1985)].

Translated by Dave Parsons