Dilepton interferometry of a quark-gluon plasma

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An interference term is predicted to exist in the inclusive cross section for the joint production of two different dileptons. It is suggested that this effect should be used for the dilepton interferometry of a quark-gluon plasma.

1. In 1959 Feĭnberg[1] showed that nuclear matter which is thermalized during a collision should emit dileptons long before it decays into secondary hadrons and that the invariant mass of these dileptons should increase as the temperature at which they are emitted is raised. Today the dilepton "thermometer" is one of the elements of the program for the detection of a quark-gluon plasma. Plasma dileptons are unavoidably screened out by the background from the hard (Drell-Yan) processes and from the meson decay and meson resonances. The detection of dileptons is therefore a necessary but not sufficient condition for the existence of a quark-gluon plasma. It must be shown that a spatial domain which is filled with a heated continuous medium that emits dileptons does actually form in a nuclear collision. Interferometry, whose applicability is contingent upon the independence of the emission of particles from different world-volume domains of the emitting system, is the most suitable tool for the detection of a plasma: a quark-gluon system in the state of a *local* thermodynamic equilibrium. It was recently shown[2,3] that the use of a pion interferometry makes it possible to accurately detect the last stage of hydrodynamic motion in nuclear matter. In the present letter we propose the use of dileptons $l\bar{l}$ for a similar study of the space-time evolution of a quark-gluon plasma.

2. Let us assume that the lepton l is detected at the point x_1 and the antilepton $\bar{l}$ is detected at the point x_2. Let us also assume that the main reaction channel is $q\bar{q}\to\gamma^*\to l\bar{l}$. The probability for the detection of $l\bar{l}$ in the lower order of perturbation theory can then be written

$$I(x_1,x_2)=\frac{e^2}{4}\int d\xi_1 d\xi_2 d\eta_1 d\eta_2 \,\mathrm{Tr}[G^{(+)}_{adv}(\xi_2,x_1)\gamma^0 G^{(+)}_{ret}(x_1,\xi_1)\gamma_\mu G^{(-)}_{adv}(\xi_1,x_2)\gamma^0$$

$$\times\, G^{(-)}_{ret}(x_2,\xi_2)\gamma_\nu]D_{ret}(\xi_1,\eta_1)D_{ret}(\xi_2,\eta_2)\sum_Q e_Q^2\langle j^\mu_{(Q)}(\eta_1)j^\nu_{(Q)}(\eta_2)\rangle, \qquad (1)$$

where $G^{(\pm)}_{\text{ret, adv}}$ and D_{ret} are the Green's functions for leptons and photons, and $\langle j_{(Q)}j_{(Q)}\rangle$ is the expectation value of the product of two quark currents. This expectation value is calculated by means of a density matrix in local equilibrium[2]

$$\rho=\prod_n\left\{e^{-(P_n u_{(n)})/T_n}\Big/\mathrm{Sp}\,e^{-(P_n u_{(n)})/T_n}\right\},$$

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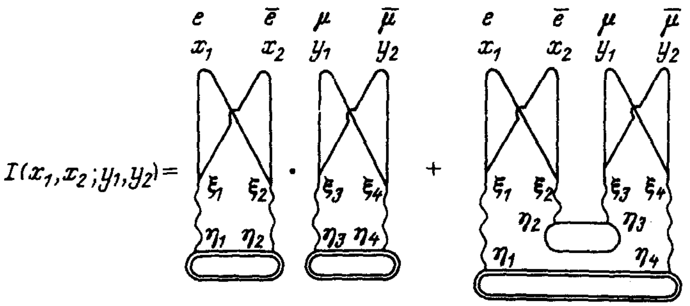

FIG. 1.

where P_n^μ is the momentum of the quark-gluon system in the nth small world volume V_n, with a temperature T_n and 4-velocity $u^\mu_{(n)}$ of the medium. Equation (1) corresponds to the unconnected diagrams in Fig. 1.

Converting to a momentum representation by means of the Wigner transform, we find the inclusive density (compare with the procedure in Ref. 4)

$$k_1^0 k_2^0 I(\mathbf{k}_1, \mathbf{k}_2) = -\frac{e^2[k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - g^{\mu\nu} k^2/2}{(2\pi)^6\ k^4} \sum_n V_n \sum_Q e_Q^2 \Pi^{(n)}_{\mu\nu}(k), \qquad (2)$$

where $k = k_1 + k_2$, and the local polarization tensor for the polarization in the volume V_n is

$$\Pi^{(n)}_{\mu\nu}(k) = (g_{\mu\nu} - k_\mu k_\nu / k^2) W_1^{(n)} + (u_\mu^{(n)} - k_\mu (ku^{(n)}))(u_\nu^{(n)} - k_\nu (ku^{(n)})) W_2^{(n)}. \quad (3)$$

The form factors $W_j^{(n)}(k)$ depend exclusively on the invariants k^2 and $(ku^{(n)})$:

$$W_j^{(n)}(k) = -\frac{\theta(k^2 - 4M^2)}{32\pi} k^2 \sqrt{1 - \frac{4M^2}{k^2}}$$

$$\times \int_{-1}^{1} \frac{e^{-(ku_{(n)})/2T_n} w_j(\xi) d\xi}{\cosh\frac{ku_{(n)}}{2T_n} + \cosh\left[\frac{\sqrt{((ku_{(n)})^2 - k^2)(1 - 4M^2/k^2)}}{2T_n}\xi\right]}$$

(4)

$$w_1 = \left(1 + \frac{4M^2}{k^2}\right) + \left(1 - \frac{4M^2}{k^2}\right)\xi^2; \quad w_2 = \left(1 - \frac{4M^2}{k^2}\right)\left(1 - \frac{(ku_{(n)})^2}{k^2}\right)^{-1}(1 - 3\xi^2),$$

where $M = M_Q$ are the masses of the annihilating quarks.

The definitive expression for the inclusive distribution of the dileptons $l\bar{l}$ is $(l = k_1 - k_2)$

$$k_1^0 k_2^0 I(\mathbf{k}_1, \mathbf{k}_2) = \frac{e^2}{(2\pi)^6 k^4} \sum_n V_n \sum_Q e_Q^2 \{ 2(k^2 + 2m^2) W_1^{(n)}(k)$$

$$+ [(lu_{(n)})^2 - (ku_{(n)})^2 + k^2] W_2^{(n)}(k) \} . \qquad (5)$$

3. The inclusive probability for a simultaneous detection of two dileptons can be written in the simplest form when the dileptons are different, i.e., when $e\bar{e}$ and $\mu\bar{\mu}$ are used. The probability distribution in the coordinate space can easily be reconstructed from the diagrams in Fig. 1. We can trace the origin of the interference: There are two ways in which the given final state of two different (!) dileptons can be reached. If we take into account that because of quark thermodynamics, the polarization loops are localized in only a small part of the world volume of the plasma, then the plasma can clearly be studied interferometrically. The interference term appears with the "boson" plus sign, since the intermediate heavy photons account for the necessary phase differences. The inclusive momentum distribution of two dileptons with momenta k_1 and k_2 for the electron pair and q_1 and q_2 for the muon pair is

$$I_{(\mu e)}(\mathbf{k}_1, \mathbf{k}_2; \mathbf{q}_1, \mathbf{q}_2) = I_{(e)}(\mathbf{k}_1, \mathbf{k}_2) I_{(\mu)}(\mathbf{q}_1, \mathbf{q}_2) + R(\mathbf{k}_1, \mathbf{k}_2; \mathbf{q}_1, \mathbf{q}_2),$$

$$R(k_1, k_2; q_1, q_2) = \frac{e^4 [k_1^\mu k_2^\nu + k_1^\nu k_2^\mu - g^{\mu\nu} k^2/2][q_1^\rho q_2^\sigma + q_1^\sigma q_2^\rho - g^{\sigma\rho} q^2/2]}{(2\pi)^{12} k_1^0 k_2^0 q_1^0 q_2^0 (k^2 q^2)^2}$$

$$\times \sum_{nn'} V_n V_{n'} \sum_{QQ'} e_Q^2 e_{Q'}^2 \Pi_{\mu\nu}^{(n)}\left(\frac{k+q}{2}\right) \Pi_{\rho\sigma}^{(n')}\left(\frac{k+q}{2}\right) \cos(k-q)(x_n - x_{n'}), \qquad (6)$$

where $k = k_1 + k_2$ and $q = q_1 + q_2$. In other words, the plasma is "probed" by the combined dilepton pulses. If the dileptons are emitted by a spherical volume of radius r_0 which is at rest, the correlation function can be written in the classical form

$$R(\mathbf{k}_1, \mathbf{k}_2; \mathbf{q}_1, \mathbf{q}_2) = K(k_j, q_j, T)[j_1(|\mathbf{k} - \mathbf{q}| r_0)/|\mathbf{k} - \mathbf{q}| r_0]^2 , \qquad (7)$$

where $j_1(x) = (\sin x - x\cos x)/x^2$, and K is a factor which is determined by the kinematic factors and by the time-dependent plasma-cooling dynamics. Even in this very simple form the theory can be used in analyzing the collisions with a total stopping of nuclear matter, as in the case of Okonov's group,[5] for example.[1)] In these collisions the dilepton was not detected, partly because of the dominant background from the mesonic decay. A correlation treatment would probably be free of these problems, especially in the region of large invariant dilepton masses, since the timelike intermediate heavy photons have a very short lifetime, and since the probability for an interference between the dileptons from the plasma and those from the decay of secondary mesons and resonances is extremely small. We would expect that a more detailed analysis of the correlation function would allow us to distinguish the contributions from dileptons of different origins, since experimental study of the pion interferometry of hydrodynamic objects[2,3] shows that this method is very sensitive to the internal motion in the emitting system.

We note in conclusion that in analyzing the processes involving excited intermediate nuclei Grishin *et al.*[6] were first to point out that an interference can arise in a system comprised of three different particles. M. I. Podgoretskiĭ brought this fact to my attention. In contrast with our study, Grishin *et al.*[6] studied the intermediate resonances.

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[1)] According to the initial report published in the CERN Courier, such events have already been observed at SPS even at 200-A·GeV energies.

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