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DILEPTON SIGNAL OF A QCD MIXED PHASE IN ULTRARELATIVISTIC NUCLEAR COLLISIONS[1]

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The correlation between thermal dilepton emission and hadronic multiplicity is investigated to obtain the signal of a QCD mixed phase formation in ultrarelativistic nuclear collisions.

I. INTRODUCTION

There is an increasing interest in studies of the processes which might be probes of quark matter formation in ultrarelativistic nuclear collisions. One of the most attractive processes of this kind is the emission of lepton pairs. Thermal dilepton emission is an important source of information about the temperature and the quark-hadron composition of the QCD matter since lepton pairs are emitted at all stages of evolution and do not suffer rescattering [1, 2].

As the emission rate of thermal dileptons is approximately proportional to $\exp(-M/T)$ for $M \gg T$ (M is the invariant lepton pair mass, T is the temperature), heavy lepton pairs are mainly produced by a high temperature system. Thus the principle of the dilepton emission probes [3—9] of the quark-gluon plasma is as a rule an analysis of the dilepton spectra in an extremely high invariant mass region. To obtain the dominant contribution just from the quark-gluon plasma, the initial temperature T_0 of the system has to exceed considerably that of the phase transition T_c. Such an approach faces, however, some difficulties: first, the events with a very high initial temperature $T_0 \gg T_c$ may be extremely rare (of impossible at all) in the experiments carried out now, and secondly it is a complicated problem to separate thermal dileptons with large M from the Drell-Yan background.

If, on the other hand, the deconfinement of quarks is a first order phase transition, then a quark-hadron mixed phase with $T = T_c$ should exist. Quite probably the QCD matter is formed in modern accelerators with an initial temperature T_0 not much higher than the critical T_c one. Therefore, when searching for quark-gluon plasma signals with $T > T_c$, it is undoubtedly important to analyse the possible experimental probes of the QCD matter within the phase transition region.

Our aim is to study experimentally available dilepton signals of the mixed phase formation in ultrarelativistic nuclear collisions. To achieve this it seems to be useful to consider the correlation between dilepton emission and hadronic (π-meson) multiplicity in the central rapidity region. We hope this also allows to elucidate the space-time scenario of the hadronization transition.

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II. THE MODEL

Our description of the central ultrarelativistic AA nuclear collisions is based on one-dimensional scaling hydrodynamics [10]

$$v(x, t) \equiv \operatorname{th} \eta(x, t) = \frac{x}{t}, \quad s(\tau) = \frac{s_0 \tau_0}{\tau}; \quad \tau = (t^2 - x^2)^{1/2}, \tag{1}$$

where x, t are the longitudinal cooorditante and time, $v(x, t)$ is the longitudinal velocity of the fluid element (η is its rapidity), s is the entropy density whose initial values s_0 is formed at the proper time $\tau = \tau_0(\tau_0 = 1$ fm [10]). The decay of the hydrodynamical system into secondary particles is assumed to take place at the critical isoterm $T(x, t) = T^*(T^* \cong 140$ MeV). The secondary hadron (π-meson) rapidity distribution for the scaling solution (1) has the form

$$\frac{dN_\pi}{dy} = 0.27\, \pi R^2 s_0 \tau_0, \tag{2}$$

where $R \cong A^{1/3}$ fm is the transverse size of the system (in what follows we consider pion and dilepton spectra for rapidity close to zero in the c.m.s.).

We use the bag model equation of state: an ideal gas of massless u,d-quarks and gluons with vacuum nonperturbative contribution B at $T > T_c$ and an ideal π-meson gas at $T < T_c$. We fix the temperature of the 1-order phase transition as $T_c = 200$ MeV in accordance with lattice QCD calculations. At $T = T_c$ there is an abrupt jump of the energy and entropy densities

$$\Delta\varepsilon \equiv \Delta\varepsilon_Q - \varepsilon_H = 4B, \quad \Delta s \equiv s_Q - s_H = \frac{2\pi^2}{45}(\gamma_q - \gamma_h)T_c^3; \tag{3}$$

$$\gamma_q = 37, \quad \gamma_h = 3$$

and the relative volume of the quark component within the mixed phase is given by

$$\delta = \frac{s - s_H}{s_Q - s_H}.$$

The dilepton emission rate is well known to be ($M \gg T, m_l, m_\pi$):

$$\frac{dN_{l^+l^-}}{d^4x\, d^2p_\perp\, dM^2 dy} = \frac{\alpha^2}{8\pi^4} F \exp\left[-\frac{\bar{E}}{T}\right]. \tag{4}$$

where $\alpha = 1/137$; $p_\perp, y, M$ are the transverse momentum, rapidity and mass of a lepton pair; $\bar{E} = (M^2 + p_\perp^2)^{1/2} \mathrm{ch}(y - \eta)$ is its energy in the rest system of the fluid element with 4-volume d^4x and temperature $T(x, t)$. The factor F defines the elementary processes $q\bar{q} \to l^+l^-$ and $\pi^+\pi^- \to l^+l^-$ [6, 7]:

$$F = \begin{cases} F_q \equiv \sum_q e_q^2 = 5/9, & T > T_c \\ F_h \equiv \dfrac{1}{12} \dfrac{m_\varrho^4}{(m_\varrho^2 - M^2)^2 + m_\varrho^2 \Gamma_\varrho^2}, & T < T_c \\ \delta F_q + (1 - \delta) F_h, & T = T_c \end{cases} \tag{5}$$

$$m_\varrho \simeq 0.77 \text{ GeV}, \quad \Gamma_\varrho \simeq 0.15 \text{ GeV}.$$

III. CORRELATION BETWEEN DILEPTON EMISSION AND HADRONIC MULTIPLICITY

The corelation between low mass dilepton production and hadronic multiplicity was considered in [11] in the framework of the soft-annihilation model [12]. This model predicts the following relation

$$\frac{dN_{l^+l^-}}{dy} \sim \left(\frac{dN^\pi}{dy}\right)^2. \tag{6}$$

The origin of the correlation (6) in [11] is easy to understand. The total number of lepton pairs from the space-time region $\mathscr{R}$ is given by the formula

$$\frac{dN_{l^+l}}{dy} \sim n_q n_{\bar{q}} v \sigma \mathscr{R}, \tag{7}$$

where n_q and $n_{\bar{q}}$ are densities of quarks and antiquarks, v is the relative velocity and σ is the $q\bar{q} \to l^+l^-$ cross-section. Since the number of quarks and antiquarks is assumed in [11] to be proportional to the pion multiplicity $n_q \sim n_{\bar{q}} \sim dN_\pi/dy$ and $\mathscr{R}$ is supposed to be independent of dN_π/dy one obtains the correlation (6).

The soft-annihilation model describes the non-thermolized system of quarks and gluons with a time of existence essentially given by the recombination process. For the thermolized matter as it might be formed in ultrarelativistic nuclear collisions the correlation between dilepton emission and hadron multiplicity was studied in [13]. It is useful to consider this correlation in order to obtain the signal of the deconfinement phase transition. We investigate the function

$$\mathscr{K} \equiv A^{2/3} \left(\frac{dN_\pi}{dy}\right)^{-2} \frac{dN_{l^+l^-}}{dM^2 dy}. \tag{8}$$

The factors $A^{2/3}$ and $(dN_\pi/dy)^{-2}$ eliminate in (8) the "trivial" correlations arisen from the growth of the geometrical size of the one-dimensional hydrodynamic system: the transverse size $R^2 \sim A^{2/3}$, the size of the region in the $x - t$ space $(A^{-2/3} dN_\pi/dy)^2$. The remaining dependence of $\mathscr{K}$ on dN_π/dy reflects the variation of the dilepton emission due to the growth of the initial temperature in hadron or quark phases and due to the change of the quark-hadron composition in the mixed phase.

Integrating (5) over d^4x and $p_\perp$ we find ($M \gg T_0$):

$$\mathscr{K} = \frac{C}{M^4} \left\{ \lambda^2 F_h \int_{M/\min(T_0, T_c)}^{M/T^*} du\, u^{7/2} e^{-u} + \Theta(s_0 - s_H) \frac{\lambda - 1}{6} \times \right.$$
$$\left. \times [F_q Q(s_0) + \lambda F_h H(s_0)] \left(\frac{M}{T_c}\right)^{9/2} e^{-M/T_c} + \Theta(s_0 - s_Q) F_q \int_{M/T_0}^{M/T_c} du\, u^{7/2} e^{-u} \right\}; \tag{9}$$

$$\lambda \equiv \gamma_q/\gamma_h \simeq 12.3; \quad C \simeq 5.3 \times 10^{-8} \text{ fm}^{-2}$$

$$Q(s_0) = \begin{cases} (1 - s_H/s_0)^2 (1 - 1/\lambda)^{-2}, & s_H < s_0 < s_Q \\ 1, & s_0 > s_Q \end{cases} \tag{10}$$

$$H(s_0) = \begin{cases} (1 - s_H/s_0)(1 + s_H/s_0 - 2/\lambda)(1 - 1/\lambda)^{-2}, & s_H < s_0 < s_Q \\ 1, & s_0 > s_Q \end{cases} \tag{11}$$

For $s_0 > s_H$ the contribution to $\mathscr{K}$ from the pure hadron phase is saturated and the growth of the function $\mathscr{K}$ for $s_0 \in [s_H, s_Q]$ occurs because of the mixed phase "cut-in" (Fig. 1). If M is large enough so that the efficacy of the dilepton generation by a quark component is considerably higher than the hadron one ($F_q \gg F_h$), then the growth of the $\mathscr{K}$ function becomes rather appreciable. On the other hand M may not be too large because the high M region is dominated by the Drell-Yan process. In our calculation we chose $M = 2$ GeV.

For $s_0 > s_Q$ the mixed phase is fully "cut-in", which leads to a wide quasi-

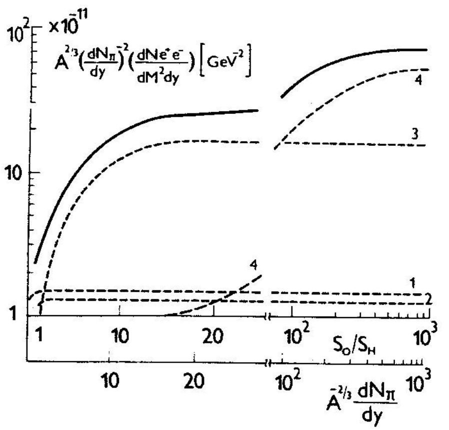

Fig. 1 The full line is $\mathscr{K} \equiv A^{2/3}\left(\frac{dN_\pi}{dy}\right)^{-2}\frac{dN_{l^+l^-}}{dM^2dy}$ versus $\frac{s_0}{s_H}$ versus $A^{-2/3}\frac{dN_\pi}{dy}$, according to (8). The dashed lines show the individual contributions to the dilepton emission from various stages of the hydrodynamic expansion: 1 is hadronic with $T < T_c$, 2 is hadronic of the mixed phase with $T = T_c$, 3 is quark of the mixed phase with $T = T_c$, 4 is the quark-gluon plasma with $T > T_c$.

plateau in the $\mathscr{K}$ dependence on dN_π/dy. The quark-gluon plasma appears as a new increase in $\mathscr{K}$ with dN_π/dy. It would be possible, however, in the events with extremely high values of $dN_\pi//dy$, which is unlikely occur in the present accelerator experiments. The peculiar increase and quasi-plateau behaviour of $\mathscr{K}(dN_\pi/dy)$ (when the contribution of the mixed phase is dominant) may be a rather good sign of the quark-hadron phase transition.

IV. CONCLUSION

We see that in the scaling of hydrodynamics there is a quadratic dependence (6), but as it is seen from Fig. 1 different phases give different values of quadratic contributions. The resulting "two-steps" behaviour of $\mathscr{K}(dN_\pi/dy)$ demonstrates the cut-in, first the mixed phase and then quark-gluon plasma. The origin of the dependence (6) in the hydrodynamical model is quite different from that in the soft-annihilation model. Taking into account space-time evolution the hydrodynamical model gives

$$\mathscr{R} \sim \bar{V}\bar{\tau} \sim \frac{dN_\pi}{dy}\cdot\frac{dN_\pi}{dy},$$

where $\bar{V}$ is the effective 3-volume of the system and $\bar{\tau}$ is its proper life time. Quark (antiquark) density is usual a Fermi ideal gas distribution, which is only

a temperature dependent function. The QCD mixed phase gives the dominant contribution to $\mathscr{K}$ in the wide range of the parameters M and dN_π/dy. The space-time scenario of hadronization transition remains, however, unknown so far. In [14] there was considered a break-up of the quark matter at the critical density ε_Q into separate droplets which independently convert into hadrons by deflagration. In this case we have $dN_{l^+l^-}/dy \sim dN_\pi/dy$ for a mixed phase contribution since the droplet life time depends on its radius and the deflagration shock velocity but does not depend on dN_π/dy.

We conclude by stating that the experimental data on the correlation between dilepton emission and hadronic multiplicity can give the signal of the deconfinement phase thransition and elucidate the hadronization transition scenario.

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ДИЛЕПТОННЫЙ СИГНАЛ СМЕШАННОЙ ФАЗЫ КХД В УЛЬТРАРЕЛЯТИВИСТСКИХ ЯДЕРНЫХ СОУДАРЕНИЯХ

Корреляция между тепловой эмиссией лептонных пар и адронной множественностью используется для получения сигнала о формировании смешанной фазы КХД материи в ультрарелятивистских ядерных соударениях.