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A Signature for the Formation of the Quark-Gluon Plasma in Nucleus-Nucleus Collisions*

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Abstract Based on thermodynamic relations, the initial values of the quark-gluon system from relativistic nucleus-nucleus collisions are obtained. Using these initial values we have studied the dilepton production on the basis of the relativistic hydrodynamic model, and found that with increasing incident energy a characteristic plateau indicating the formation of the quark-gluon plasma appears in the total yield, which may be tested in future experiments in CERN and Brookhaven.

Key words initial values of the quark-gluon plasma, hydrodynamic model, dilepton

The relativistic heavy ion collision is very significant to test whether the quark-gluon plasma (QGP) exists and further to study the properties of QGP. It is very helpful to comprehend the mechanism of confinement, the early universe in the cosmic evolution and so forth. Many laboratories such as CERN SPS and RHIC are performing or preparing experiments to search for the QGP.

The dilepton production for baryon-free quark-gluon plasma (QGP) has been studied previously[1,2]. Experiments and theories have indicated that the colliding heavy ions may not be fully transparent[3,4]. Consequently, it is possible that the baryon density in the QGP does not vanish for heavy ions collisions at those"moderate" energies. Dumitru et al.[3] have studied the dilepton production from a QGP of given energy density at finite quark chemical potential. Ko et al.[5] Have calculated the dilepton production for baryon-rich QGP via a hydro-chemical description of heavy ion collisions. Recently, the dilepton production in an expanding baryon-rich QGP fireball has been studied[6]. However, the initial values for baryon-rich QGP system, i. e. the initial temperature and initial quark chemical potential. are still an open problem, which are conerstones of theoretical calculations and should be considered at first. Xia et al. have discussed the initial values of the system in Ref. [7] Authors of Ref. [8] determined the initial temperature only by the entropy, then obtained the chemical potential by this initial temperature via a parametrization of the relativistic quantum molecular dynamics calculation [9]. In Refs. [10,11], the initial values were determined by fitting the final pion or proton rapidity distributions and transverse momentum spectra to available experimental data after the full dynamical evolution of the system. Obviously, initial values obtained are strongly model-dependent. In Refs. [2,6,12] HE ZeJun et al. have obtained qualitative signatures for the QGP formation, but the initial values were not considered in detail.

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In this letter, using the initial values obtained from the incident energy based on the thermodynamic relations, we have studied the dilepton production in a baryon-rich QGP fire-cylinder to give the characteristic physical quantities for the formation of the QGP matter, and then, compared the results with those obtained in the baryon-rich QGP fireball so as to see the dependence of the production on the model. It is worth emphasizing here that we only calculate dileptons with intermediate invariant masses, i. e. $1.2\,\text{GeV} < M < 2.8\text{GeV}$, thus the contribution from Drell-Yan mechanism should be included, but those from hadronic resonances produced in initial nucleus-nucleus collisions may be neglected.

We have first calculated the initial values of the system via the thermodynamic relations. For the QGP system, considering only light quarks u, d, with the help of MIT bag model the energy density of the system ε is given by[8]

$$\varepsilon = 3p_{qg} + 4B, \tag{1}$$

where p_{qg} is the pressure of the QGP system, B the bag constant. For the hadron phase when it is the normal nuclear matter with saturation density and zero pressure, saturation energy density ε_0 is given by $\varepsilon_0 = 4B$. The energy density ε_{in}, related to the temperature in the initial QGP phase, is thus $\varepsilon_{in} = \varepsilon - \varepsilon_0 = 3p_{qg}$. Multiplying the volume V, we obtain the following relation

$$\frac{1}{3}(\varepsilon - \varepsilon_0)V = \frac{1}{3}\varepsilon_{in}V = p_{qg}V, \tag{2}$$

The work done on the external system, which is equivalent to the reduction of the internal energy in an adiabatic process, equals to $p_{qg}V$, and hence the total energy entering into the QGP system $E_{in} = \frac{4}{3}\varepsilon_{in}V$. For the very high temperature case, the phase-space distribution function can be replaced by its Boltzmann approximation. If the initial particle number is given, the initial temperature T_{q0} can be defined by the principle of equipartition of energy,

$$\frac{3}{4}E_{in} = \frac{3}{2}NT_{q0}, \tag{3}$$

where N is the total particle number of the system, which includes the total number of sea quarks, valence quarks and gluons. Solving the set of coupled equations 2 and 3, the initial temperature T_{q0} and the initial chemical potential μ_{q0} are obtained.

As pointed out in Refs. [2,6,12,13], once local thermodynamic equilibrium of the system is established, the further expansion of the system is governed by conservation relations of the energy-momentum, baryon number and entropy. Using some useful thermodynamic relations, we have obtained a set of coupled relativistic hydrodynamic equation (RHE) describing the evolution of a cylindrically symmetric baryon-rich QGP fire-cylinder

$$\partial_t(\gamma s) + \frac{1}{r}\partial_r(r\gamma s v_r) + \partial_z(s\gamma v_z) = 0 \tag{4}$$

$$\partial_t(\gamma n) + \frac{1}{r}\partial_r(r\gamma n v_r) + \partial_z(n\gamma v_z) = 0 \tag{5}$$

$$\begin{aligned} &s[\partial_t(T\gamma v_r) + \partial_r(T\gamma) + v_z(\partial_z(T\gamma v_r) - \partial_r(T\gamma v_z))] + \\ &n[\partial_t(\mu_b\gamma v_r) + \partial_r(\mu_b\gamma) + v_z(\partial_z(\mu_b\gamma v_r) - \partial_r(\mu_b\gamma v_z))] = 0 \end{aligned} \tag{6}$$

$$\begin{aligned} &s[\partial_t(T\gamma v_z) + \partial_z(T\gamma) - v_r(\partial_z(T\gamma v_r) - \partial_r(T\gamma v_z))] + \\ &n[\partial_t(\mu_b\gamma v_z) + \partial_z(\mu_b\gamma) - v_r(\partial_z(\mu_b\gamma v_r) - \partial_r(\mu_b\gamma v_z))] = 0, \end{aligned} \tag{7}$$

where v_r and v_z are, respectively, velocity components in the transverse and longitudinal directions, γ the Lorentz contract factor. μ_b the baryon chemical potential and T the temperature.

As pointed out above, we have only studied dileptons with the intermediate invariant masses. Therefore, the dilepton background from Drell-Yan mechanism produced in initial nucleus-nucleus collisions should be considered[8,14]. For the quark phase, dileptons are dominantly from $q\bar{q}$ annihilations, and for the hadronic phase from $\pi^+\pi^-$ annihilations. According to Ref. [8] the dilepton yield from the $q\bar{q}$ is given by

$$\frac{dN^q}{d^4x dM_T^2 dM^2 dY} = \frac{\alpha^2}{8\pi^3} F_q \exp\left[-\frac{M_T ch(Y-\eta)}{T}\right] J_q, \qquad (8)$$

where rapidity Y, transverse mass M_T is defined in the four-momentum of dilepton $q_\mu = (M_T \mathrm{ch} Y, q_T, M_T \mathrm{sh} Y)$ with q_T the transverse momentum and $M_T = \sqrt{M^2 + q_T^2}$. $F_q = \frac{5}{9}$ is the form-factor for both u, d quarks. The space-time element $d^4x = 2\pi r dr dz dt$ for the fire-cylinder. The factor J_q relates to the non-zero quark chemical potential. For the hadronic phase, the dominant contribution from $\pi^+\pi^-$ annihilations is given by

$$\frac{dN^q}{d^4x dM_T^2 dM^2 dY} = \frac{\alpha^2}{8\pi^3} F_h \exp\left[-\frac{M_T \mathrm{ch}(Y-\eta)}{T}\right], \qquad (9)$$

where

$$F_h = \frac{1}{12} m_\rho^4 [(m_\rho^2 - M^2)^2 + m_\rho^2 \Gamma_\rho^2]^{-1} \qquad (10)$$

with $m_\rho = 0.77\mathrm{GeV}$, $\Gamma_\rho = 0.15\mathrm{GeV}$.

We have first calculated the phase boundary for the bag constant $B^{1/4} = 250\mathrm{MeV}$ by the Gibbs conditions, as done in Ref. [6], then, using calculated initial values, obtained the temperature and quark chemical potential distributions in the space-time via solving the RHE in the μ-T phase diagram, and finally, calculated dilepton yields. In this letter, in order to relate with experiments in RHIC we have studied the dependence of dilepton production on the rapidity Y, dilepton invariant mass M and incident energy E_{in}/N_A for ^{197}Au + ^{197}Au central collisions, where E_{in} is the total incident energy, N_A the total nucleon number of the colliding nuclei.

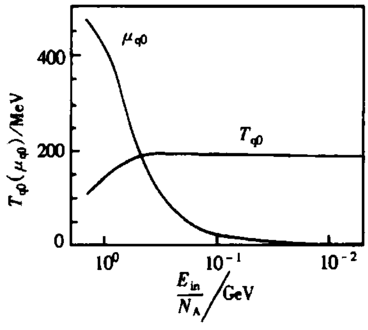

Fig. 1. The dependence of the initial temperature T_{q0} and initial quark chemical potential μ_{q0} of the baryon-rich QGP on the incident energy E_{in} at the bag constant $B^{1/4} = 250\mathrm{MeV}$.

The calculated initial temperature T_{q0} and initial quark chemical potential μ_{q0}, as functions of the energy E_{in}/N_A, are shown in Fig. 1. For the QGP system with increasing incident energy, the particle number of the system such as gluons, quarks and anti-quarks rapidly goes up. In the QGP system the incident energy E_{in} partly converts into the kinetic energy for the expansion of the system, and is partly dissipated to excite more particles. Thus, the increase of the temperature is suprssed, making a plateau as seen in Fig. 1.

We have calculated the dilepton yield dN/dM^2dY, as shown in Fig. 2, where curves 1 to 5 denote, in turn, the yields at rapidities $Y = 0.0, 0.5, 1.0, 1.5, 2.0$. From previous works[1,2,5] one can see that the humps of the hadronic phase contribution to the spectrum are very obvious. However, in this work, since both the temperature and the quark chemical potential are functions of space-time, it necessarily takes a long time for values

(μ_q, T) of various local regions of the system to reach values of the phase boundary at different times to make various local phase transitions. Such effects delay the evolution process of the QGP, increase the lifetime of the QGP and hence heighten largely the contribution of the QGP. On the other hand, due to these effects the most local phase transitions occur at lower temperatures and higher baryon chemical potentials, where the antiquark density becomes very low, leading the very low dilepton yield from quark-anti-quark pair annihilations. In this case, after transition the temperature of the hadronic phase is still very low, thus the contribution of the hadronic phase to the dilepton is so small that the hump of the hadronic phase contribution is submerged by the one from the quark phase. For these reasons, curves 1 to 5 in Fig. 2 are without obvious humps of the pion contribution.

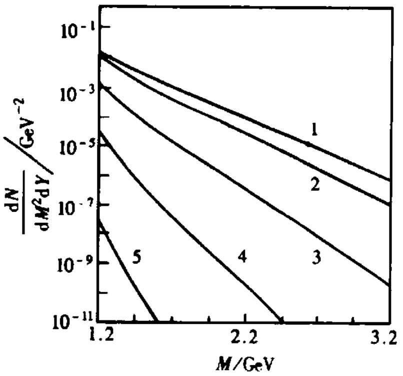

Fig. 2. The dilepton yield dN/dM^2dY as a function of the incident energy for a baryon-rich QGP fire-cylinder at the incident energy $E_{in}/N_A = 20$ GeV

Curves 1 to 5 denote in turn. the yields at rapidities $Y = 0.0, 0.5, 1.0, 1.5, 2.0$.

Subsequently, from the view point of the experiment, we have further calculeted the total dilepton yield N(solid line), as demonstrated in Fig. 3. For comparison, the result (dashed line) for fireball has been calculated and shown in Fig. 3, too. These excitation functions of the dilepton production in the baryon-rich QGP have been obtained through the relation between the distribution of the temperature (and also the quark chemical potential) and the incident energy. Though there exists some difference between these two results, both of them have shown that once the QGP was created in collisions a characteristic plateau necessarily appears in the total dilepton yield.

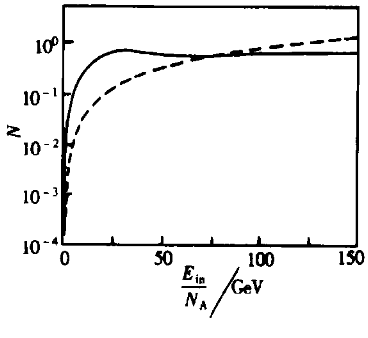

Fig. 3. The total dilepton yield N as a function of the incident energy

The solid line is for the fire-cylinder, and the dashed line for the fireball under the same conditions as given in Fig. 2.

In conclusion, in this work, from thermodynamic equilibrium, we have established the formalism for calculating initial values of the evolution of the baryon-rich QGP system, and obtained the relation between the dilepton production and the incident energy, which is advantageous to the comparison between the theoretical and experimental results. Then using initial values obtained we have calculated dilepton yields based on the two geometrical models. These two results both indicate that with increasing incident energy a characteristic plateau appears in the total dilepton yield of the baryon-rich QGP. This characteristic for the formation of the baryon-rich QGP can be tested in the future experiments at CERN and Brookhaven. It is worth emphasizing here that it is necessary to consider the geometrical model, but the qualitative features of our results should persist.

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References

1 Kajantie K, Kapusta K, Melerran L D et al. Phys. Rev., 1986, **D34**: 2747
2 HE ZeJun, ZHANG JiaJu, LI PanLi et al. Nucl. Phys., 1991, **A532**: 743
3 Dumitru A, Rischke D H et al. Phys. Rev. Lett., 1993, **70**: 2860
4 Möhring H J, Ranft J. Z.Phys., 1991, **C52**: 643
5 KO C M, XIA L H. Phys. Rev. Lett., 1989, **62**: 1595
6 HE ZeJun, ZHANG JiaJu, QIU XiJun et al. Nucl. Phys., 1997, **A614**: 552
7 XIA L H, KO C M, LI C T. Phys. Rev., 1990, **411**: 572
8 Kämpfer B, Pavlenko O P, Gorenstein M I et al. Z. Phys., 1995, **A353**: 71
9 Sorge H, Stöcker H, Griner W. Nucl. Phys., 1989, **A498**: 567c
10 LI. G. Q, KO C M, Brown G E. Phys. Rev. Lett., 1995, **75**: 4007
11 Sollfrank J, Huovinen P, Kataja M et al. Phys. Rev., 1997, **C55**: 392; Chin. Phys. Lett., 1997, **14**: 577
12 HE ZeJun, ZHANG JiaJu et al. Chin. Phys. Lett., 1999, **16**: 259
13 Baym G, Friman B L, Blaizot J P et al. Nucl. Phys., 1983, **A407**: 541
14 Vogt R, Jacak B V. McGaughey P L et al. Phys. Rev., 1994, **D49**: 3345

夸克－胶子的等离子体在核－核碰撞中形成的信号*

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摘要 从热力学关系，得到来自相对论核碰撞形成的夸克-胶子系统的初始值．基于这些初始值，在相对论流体力学模型下研究了双轻子的产生，发现随着入射能量的增加，一个标志夸克-胶子等离子体形成的特征平台出现在总产额中．这些特征可在CERN(西欧中心)和Brookhaven未来的实验中得到检验．

关键词 夸克-胶子等离子体的初始值，流体力学模型，双轻子

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