Dilepton production in baryon-rich quark-gluon matter*

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Abstract From the full stopping scenario and considered the Drell-Yang background, the rapidity dependence of the dilepton production from the central collision ^{197}Au + ^{197}Au has been studied in the baryon-rich quark-gluon matter by using a relativistic hydrodynamic model. It can be found that the dilepton yield is strongly suppressed as increasing the rapidity. Such a characteristic signaling the formation of the baryon-rich quark-gluon matter can be tested in future experiments at CERN and Brookhaven.

Keywords Relativistic heavy-ion collisions, Hydrodynamic equation, Rapidity dependence of dilepton production

1 Introduction

The dilepton production for baryon-free quark-gluon matter (QGM) has been studied previously.[1,2] Recent experiments and theories indicate that the colliding heavy ions may not be fully transparent.[3,4] It means that the dilepton production depends on both the temperature and the baryon density. Dumitru *et al*[3] have studied the dilepton production for given energy density at a finite baryon chemical potential. Ko *et al*[5] reported the dilepton production for baryon-rich QGM via a hydrodynamic description of heavy-ion collisions, in which the spatial average of the hydrodynamic equations was adopted. Recently authors have studied the dilepton production in an expanding baryon-rich quark-gluon fireball.[6]

Based on the results in literatures mentioned above, the rapidity dependence of dilepton production has been studied in baryon-rich QGM system with cylindrical transverse expansion accompanying a longitudinal expansion and some results are reported in this paper.

2 The rapidity dependence of dileptons

With the help of the dilepton yield expressions given in Refs.[7,8] for the quark phase, the dilepton yield, which is dominantly for $q\bar{q}$ annihilations, can be given by

$$\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}M_T^2\mathrm{d}M^2\mathrm{d}Y} = \frac{\alpha^2}{8\pi^3}F_q \cdot \exp\Big[-\frac{M_T\mathrm{ch}(Y-\eta)}{T}\Big]J_q \tag{1}$$

where $q^\mu = (M_T\mathrm{ch}Y, q_T, M_T\mathrm{sh}Y)$ is the four-momentum of dilepton pairs with rapidity Y, invariant mass M and transverse mass M_T. F_q is the form factor for u, d quarks, and η denotes the flow rapidity, $\mathrm{d}^4x = \mathrm{d}^2x_T\mathrm{d}\eta\tau\mathrm{d}\tau$, where x_T is the transverse coordinate. The factor J_q relates to the non-zero chemical potential of quarks. For the hadronic phase, dilepton production for $\pi\pi$ annihilation is calculated by

$$\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}M_T^2\mathrm{d}M^2\mathrm{d}Y} = \frac{\alpha^2}{8\pi^3}F_h \cdot \exp\Big[-\frac{M_T\mathrm{ch}(Y-\eta)}{T}\Big] \tag{2}$$

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where the form factor for hardon $F_h = \frac{1}{12}m_\rho^4[(m_\rho^2 - M^2)^2 + m_\rho^2\Gamma_\rho^2]^{-1}$, m_ρ=0.77 GeV and Γ_ρ=0.15 GeV. Since processes like $\pi N \longrightarrow N + l\bar{l}$, $\pi N \longrightarrow \Delta + l\bar{l}$ and $NN \longrightarrow l\bar{l}$ provide smaller contributions to the dilepton rate, they are neglected. Subsequently, we can get yield dN/dM^2dY via integrating Eqs.(1) and (2) over space-time and transverse mass.

In the intermediate invariant mass and larger rapidity region the background from Drell-Yan mechanism, dN^{DY}/dM^2dY, should not be neglected. In our calculation, the rapidity dependence of Drell-Yan background in the central collisions is taken into account based on the Duke-Owens structure functions 1.1.[9]

3 The evolution of the QGM system

As pointed out in Ref.[10], once local thermodynamic equilibrium of the system is established, the further expansion of the system is governed by the energy-momentum conservation law $\partial_\mu(T^{\mu\nu})$=0. Further considering conservation for baryon number and entropy, i.e. $\partial_\mu(nu^\mu)$=0 and $\partial_\mu(su^\mu)$=0, using thermodynamic relations $d\varepsilon = Tds + \mu_b dn$ and $dp = sdT + nd\mu_b$, and following Ref.[10], a set of coupled relativistic hydrodynamic equation (RHE) for the cylindrical transverse expansion accompanying the longitudinal expansion can be obtained as followings

$$\partial_t(rt\gamma s) + \partial_r(rt\gamma s \cdot \tanh\eta) = 0 \tag{3}$$

$$\partial_t(rt\gamma n) + \partial_r(rt\gamma n \cdot \tanh\eta) = 0 \tag{4}$$

$$\begin{aligned} &Ts[\sinh\eta\partial_t\ln T + \cosh\eta\partial_r\ln T + \sinh\eta\partial_r\eta + \cosh\eta\partial_t\eta] \\ &+\mu_b n[\sinh\eta\partial_t\ln\mu_b + \cosh\eta\partial_r\ln\mu_b + \sinh\eta\partial_r\eta + \cosh\eta\partial_t\eta] = 0 \end{aligned} \tag{5}$$

where γ stands for the Lorentz contract factor, η the flow rapidity, μ_b the chemical potential of the baryon, s the entropy density and n the baryon density. Since the hydrodynamic equations preserve the Lorentz-invariant character of the initial boundary conditions, the longitudinal expansion obeys a simple scaling solution[10]: $s(\tau) = s_0\tau_0/\tau$ and $v_z = z/t$, the coupling of the longitudinal and transverse motion is greatly simplified, where v_z is the longitudinal flow velocity. Thus the transverse motion for any z can be found from the central slice at z=0 by a lorentz boost in the z direction.

To solve RHE, we should first find the equation of state (EOS) of the system. Following Ref.[6], the EOS of the quark phase is obtained via a phenomenological MIT-bag model, considering only light quarks u, d, and taking the quark mass m_q=0; the EOS of the hadronic phase, including only nonstrange stable hadrons such as pions, nucleons and etas, and neglecting their interactions, is obtained.

It is shown that some strange results appear when describing the phase transition via shock wave decided by the conservation laws.[11] In this work, following Ref.[11], we consider a scenario for the phase transition, assuming that the structural rearrangement during the transition from QGM to hadronic matter needs a finite time comparable with the time of the fast relativistic collision, the transition can be modeled qualitatively as a relaxation process during baryon transition from the quark phase to the hadronic phase. Thus, the phase transition can be described by a relaxation equation.[11,12]

$$\frac{dn_b^q(t)}{dt} = -\frac{1}{\tau_{\rm intr}(t)}[n_b^q(t) - \overline{n}_b^q] \tag{6}$$

where n_b^q is the baryon density of the quark phase, $\overline{n}_b^q$ the equilibrium value given by the Fermi distribution. Taking $n_b^h(t)$ as the baryon density of the hadronic phase, we obtain the total baryon density in the transition region (i.e. mixed phase) $n_b = n_b^q + n_b^h$. The volume ratios of the quark phase and hadronic phase in the transition region can be, in turn, expressed by $\alpha_q = n_b^q/n_b$ and $\alpha_h = (1 - \alpha_q)$, from which the EOS of the transition region can be obtained. The intrinsic equilibration time has been estimated within a Fermi gas model, $\tau_{\rm intr}(t) = 2 \times 10^{-22}{\rm s}\cdot{\rm MeV}/\varepsilon^*(t)$ [2,3], where ε^* is the excitation energy per baryon of the quark phase.

Obviously, here the transition is described only through the change in the occupation number of the baryon in the quark phase due to collisions from the residual interactions.[13]

4 Results and discussions

Fist, the phase boundary for different bag constants is calculated as done in Ref.[6]. Then by using the EOS, and initial temperature and quark chemical potential which are calculated following Ref.[14], the temperature and quark chemical potential distribution in the space-time are obtained from solving the RHE in the $\mu_b - T$ phase diagram. Finally, according to Eqs.(1) and (2) dilepton yields are available.

The dilepton spectra $dN/\mathrm{d}M^2\mathrm{d}Y$ are shown in Fig.1. As pointed out in Ref.[6], for the baryon-rich QGM the most local phase transitions occur at lower temperatures and higher baryon chemical potentials, where the anti-quark density becomes very low, leading the very low dilepton yield. In this case the temperature of the hadronic phase is still very low after the phase transition. Thus the contribution of the hadronic phase to the dilepton production is so small that the hump of the hadronic phase contribution is submerged by the contribution from the quark phase. Due to these reasons curves 1 to 6 in Fig.1 are without humps of the pion contribution at lower invariant mass region. While we also see in Fig.1 that with increasing the rapidity the dilepton yield is strongly suppressed because the increase in the rapidity makes the quark chemical potential (i.e. anti-quark density) go down.

At the same rapidities as given in Fig.1 the dilepton spectra including the drell-Yan background are shown in Fig.2. Comparing Fig.2 with Fig.1 it can be seen clearly that with increasing the invariant mass the Drell-Yan background obviously affects the spectra at larger invariant masses, leading spectra to go up at medium invariant mass region.

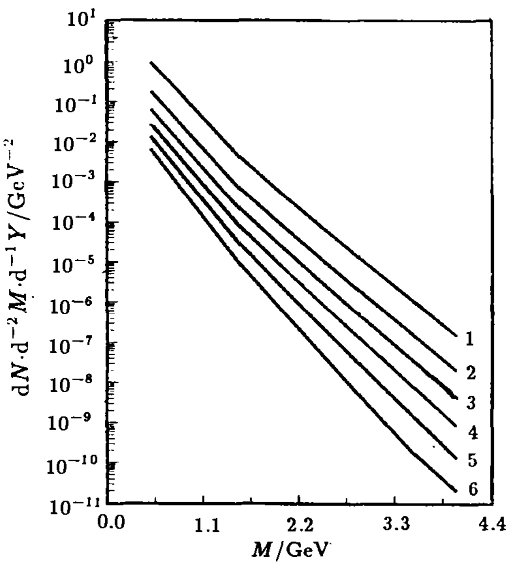

Fig.1 The calculated dilepton spectra $\mathrm{d}N/\mathrm{d}M^2\mathrm{d}Y$ for the evolution of the system in the phase diagram with the phase boundary at bag constant $B^{1/4}$=250 MeV. Curves 1 to 6 denote, in turn, the spectra at rapidities Y=1.0, 1.5, 2.0, 2.5, 3.0 and 3.5

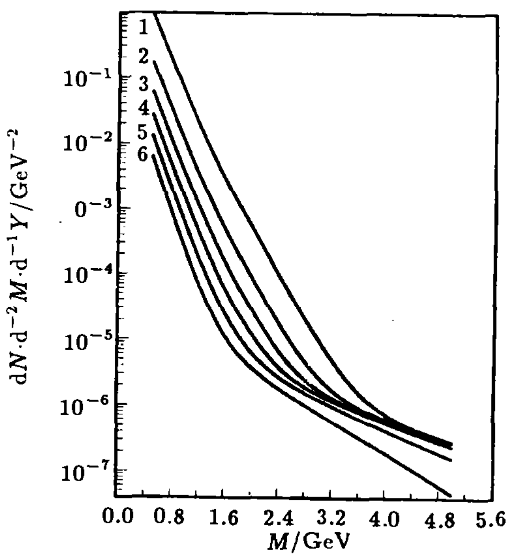

Fig.2 The calculated dilepton spectra $\mathrm{d}N/\mathrm{d}M^2\mathrm{d}Y$ including the Drell-Yan background. Curves 1 to 6 denote, in turn, the spectra at rapidities Y=1.0, 1.5, 2.0, 2.5, 3.0 and 3.5

From an experimental interest the total dilepton yield dN/dY is also calculated via integrating yields given in Fig.2 over the invariant mass. As shown in Fig.3, the total yield dN/dY goes done with increasing the rapidity. It shows again that with increasing the rapidity the dilepton production is obviously suppressed.

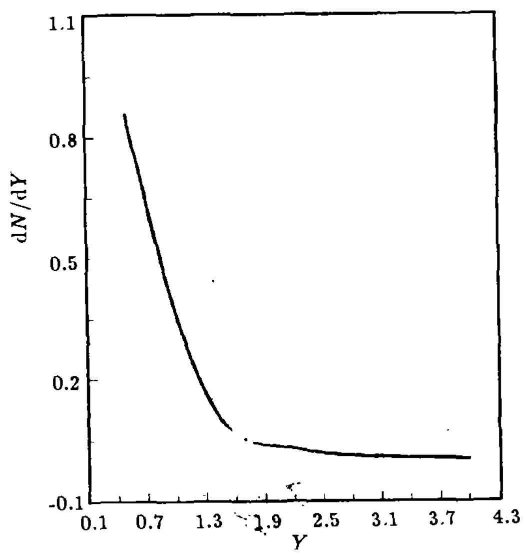

Fig.3 The total dilepton yield dN/dY including the Drell-Yan background as a function of the rapidity Y

In conclusion, if baryon-rich QGM was created, the dilepton spectrum appears without the hump of the contribution of the hadronic phase due to the effect of the phase boundary on the evolution of the system. In particular, with increasing the rapidity a obvious suppression of the dilepton yield appears at large rapidities owing to the finite baryon density. From the discussions on the background in Refs.[2,5], it can be know the background from np bremsstrahlung and Dalitz decay is not important. Our calculated results signaling the baryon-rich QGM formation thus can be directly compared with future experimental values at CERN and Brookhaven laboratory.

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