Dilepton as a signature for baryon-rich quark-gluon matter*

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Abstract Considered the Drell-Yan background in the intermediate invariant mass region, the dilepton production in an expanding hot baryon-rich quark-gluon matter fire-cylinder has been studied based on a previously established relativistic hydrodynamic model. It is found that with increasing the rapidity the dilepton yield is strongly suppressed. Such a characteristic, signaling the formation of the baryon-rich quark-gluon matter, can be tested in future experiments at Brookhaven and CERN.

Keywords Ultrarelativistic heavy-ion collisions, Quark-gluon matter, 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] Consequently, it is possible that the baryon density in the QGM does not vanish for heavy-ion collisions at those "moderate" energies. Dumitru *et al*[3] have studied the dilepton production from a QGM of given energy density at finite quark chemical potential. Ko *et al*[5] reported the dilepton production for baryon-rich QGM via a hydrochemical 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 QGM fireball.[6]

In this work, from an experimental viewpoint, based on a relativistic hydrodynamic model, we studied the rapidity dependence of dileptons with intermediate invariant mass, produced in an expanding hot baryon-rich QGM fire-cylinder.

2 Evolution of QGM

As pointed out in Ref.[7], once local thermodynamic equilibrium of the system is established, the further expansion of the system is governed by the energy-momentum conservation laws $\partial_\mu(T^{\mu\nu})=0$.[8] Further considering conservations 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 $dp=sdT+nd\mu_b$, for the evolution of a cylindrically symmetric baryon-rich QGM system formed in $^{197}Au+{}^{197}Au$ central collisions, we have obtained a set of coupled relativistic hydrodynamic equations (RHE) in non-covariant notation

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

$$\partial_t(\gamma n)+\frac{1}{r}\partial_r(r\gamma n v_r)+\partial_z(n\gamma v_z)=0 \tag{2}$$

$$s[\partial_t(T\gamma v_r)+\partial_r(T\gamma)+v_z(\partial_z(T\gamma v_r)-\partial_r(T\gamma v_z))]$$
$$+n[\partial_t(\mu_b\gamma v_r)+\partial_r(\mu_b\gamma)+v_z(\partial_z(\mu_b\gamma v_r)-\partial_r(\mu_b\gamma v_z))]=0 \tag{3}$$

$$s[\partial_t(T\gamma v_r)+\partial_z(T\gamma)-v_r(\partial_z(T\gamma v_r)-\partial_r(T\gamma v_z))]$$
$$+n[\partial_t(\mu_b\gamma v_z)+\partial_z(\mu_b\gamma)-v_r(\partial_z(\mu_b\gamma v_r)-\partial_r(\mu_b\gamma v_z))]=0 \tag{4}$$

*The Project Supported in part by 95' Key Project Funds of the Chinese Academy of Sciences (KJ 951-A1-410)
Manuscript received date: 1998-07-07

where $v = (v_r^2 + v_z^2)^{1/2}$=tanh$\eta$ is the fluid velocity, v_r and v_z are, respectively, velocity components in the transverse and longitudinal directions, η the fluid rapidity, $\gamma=(1 - v^2)^{1/2}$ the Lorentz contract factor and μ_b the baryon chemical potential.

To solve RHE, we should first find the equation of state (EOS) for 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.

In this work, the system evolves in space-time and its thermodynamic quantities are functions of space-time, hence, it is difficult to describe the process of the phase transition via the mixed phase as given by previous reports.[1,5] We propose a scenario for the phase transition as done in Ref.[6]. Assuming that the local hadronization rate of the system is so large when the (μ_b, T) of the local QGM reaches the phase boundary, a sudden local transition to the hadronic matter occurs at the temperature T_h, baryon density n_{bh} and fluid velocity v_h occurs. Thus, the continuity conditions for the energy, momentum and baryon flux densities at the discontinuity are, in turn, given by

$$T_q^{01}(T_q, \mu_{bq}, v_q) = T_h^{01}(T_h, \mu_{bh}, v_h) \quad (5)$$

$$T_q^{11}(T_q, \mu_{bq}, v_q) = T_h^{11}(T_h, \mu_{bh}, v_h) \quad (6)$$

and

$$N_q(T_q, \mu_{bq}, v_q) = N_h(T_h, \mu_{bh}, v_h) \quad (7)$$

The flux densities T_q^{01}, T_q^{11} and N_q behind the discontinuity have been decided by the temperature T_q, baryon chemical potential μ_{bq} and velocity v_q in the quark phase. Therefore, the temperature T_h, baryon chemical potential μ_{bh} and fluid velocity v_h in the flux densities in front of the discontinuity can be obtained via solving the conditions of continuity above, which are initial values in the hadronic phase.

For the evolution of the QGM system, two extreme scenarios are the full stopping model[9] and the full scaling expansion model[10]. Since the present experiments fall between these limits, we should develop parameterizations which span the range between two extremes. We consider zero impact parameter cylindrically symmetric collisions only, do not expect significant collective motion and thus take the initial radial velocity v_r=0. We have adopted the treatment as done in Ref.[11], considering a non-zero initial velocity in the longitudinal direction, v_z=tanh(z/t_0), where t_0 is a constant, which is taken so as to be able to extrapolate the velocity smoothly to unity in the outer parts. In order to find the rapidity dependence of the dilepton production, we adopt the following relation between the initial temperature (also initial quark chemical potential) and the rapidity, as given in Ref.[12]

$$T_0(Y) = [s_0(Y)\{\frac{4}{3}\frac{37}{30}\pi^2 + 2b^2Y^{2a}\}^{-1}]^{1/2} \quad (8)$$

where parameters a=1.8, b=0.15. Corresponding initial quark chemical potential $\mu_{q0}(Y) = bY^aT$.

In evolution processes, the distributions are always cut off smoothly when the space boundary is approached. Smoothing also help to avoid oscillations in the numerical calculations. Thus, parametrized initial distributions of the temperature and baryon density are given, respectively, by

$$T(r, z, 0) = T_0\exp\{-[(r/R_0)^N + (z/z_0)^N]\} \quad (9)$$

$$n_b(r, z, 0) = n_{b0}\exp\{-[(r/R_0)^N + (z/z_0)^N]\} \quad (10)$$

where N is a free parameter. For N=9, we can obtain a nearly canstant temperature and baryon density distributions in the initial fire-cylinder. To be able to solve the RHE, we, practically, have adopted the initial values obtained via suitably varying initial distributions from Eqs.(9) and (10).

3 Dilepton production

With the help of the dilepton yield expression given in Refs.[7,8], for the quark phase, dilepton yield dominantly from $q\bar{q}$ annihilations can be written in the following form

$$\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}M_\mathrm{T}^2\mathrm{d}M^2dY}=\frac{\alpha^2}{8\pi^3}F_\mathrm{q}\exp[-\frac{M_\mathrm{T}\mathrm{ch}(Y-\eta)}{T}]J_\mathrm{q} \tag{11}$$

where $q^\mu = (M_\mathrm{T}\mathrm{ch}Y, q_\mathrm{T}, M_\mathrm{T}\mathrm{sh}Y)$ 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 $\eta=\tanh^{-1}v$ the flow rapidity and $\mathrm{d}^4x=2\pi r\mathrm{d}r\mathrm{d}z\mathrm{d}t$ for the cylindrically symmetric system. The factor J_q relates to the non-zero chemical potential of quarks. For the hadronic phase, only the contribution from $\pi\pi$ annihilations is dominant and is calculated by

$$\frac{\mathrm{d}N}{\mathrm{d}^4x\mathrm{d}M_\mathrm{T}^2\mathrm{d}M^2\mathrm{d}Y}=\frac{\alpha^2}{8\pi^3}F_\mathrm{h}\exp[-\frac{M_\mathrm{T}\mathrm{ch}(Y-\eta)}{T}] \tag{12}$$

where the form factor $F_\mathrm{h}=\frac{1}{12}m_\rho{}^4[(m_\rho{}^2-M^2)^2+m_\rho{}^2\Gamma_\rho{}^2]^{-1}$, m_ρ=0.77 GeV and Γ_ρ=0.15 GeV. In addition, the process $J/\psi\longrightarrow l\bar{l}$ is also considered since it contributes a peak near M=3.10 GeV.

As well known, in the intermediate invariant mass region the background from Drell–Yan mechanism should not be neglected. Our calculations for the rapidity dependence of Drell–Yan pairs in the central collisions are performed based on the Duke–Owens structure functions 1.1.[13]

4 Results and discussion

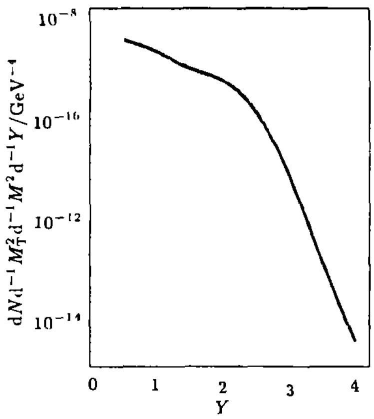

Fig.1 The calculated dilepton yield $\mathrm{d}N/\mathrm{d}M_\mathrm{T}^2\mathrm{d}M^2\mathrm{d}Y$ as a function of the rapidity Y for the evolution of the system in the phase diagram with the phase boundary 2 at transverse mass M_T=4 GeV and invariant mass M=3 GeV

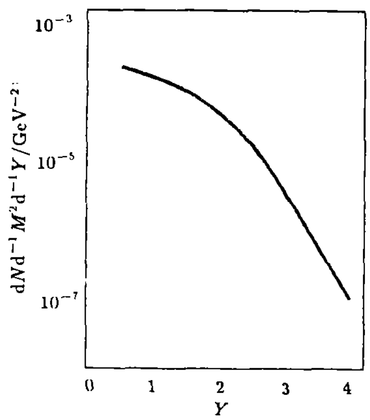

Fig.2 The calculated dilepton yield $\mathrm{d}N/\mathrm{d}M^2\mathrm{d}Y$ as a function of the rapidity Y at invariant mass M=3 GeV for the evolution of the system in the phase diagram with the phase boundary 2

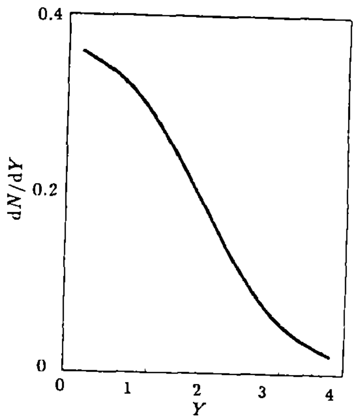

Fig.3 The calculated dilepton invariant mass spectra $\mathrm{d}N/\mathrm{d}Y$ including the Drell-Yan background for the evolution of the system in the phase diagram with the phase boundary 2

The phase boundary for different bag constants is first calculated as shown in Ref.[6]. Then, using the EOS and initial values, the temperature and quark chemical potential distributions in space-time are obtained from solving the RHE in the μ_q-T phase diagram. Finally, dilepton yields, for the system formed from ^{197}Au +^{197}Au central collisions at RHIC energies, are calculated.

The calculated rapidity distribution of dilepton yields $dN/dM_T^2dM^2dY$ at the transverse mass $M_T=4\,GeV$ and invariant mass $M=3\,GeV$ have been shown in Fig.1. While the dilepton yields dN/dM^2dY as a function of the rapidity Y have also been calculated and shown in Fig.2. The results clearly show that with the increasing of rapidity the dilepton production is strongly suppressed. To further understand the suppression of the dilepton production versus the rapidity, the dilepton yields dN/dY including the Drell-Yan background have been also calculated, as shown in Fig.3.

In conclusion, if the baryon-rich QGM has indeed been created in collisions, according to the relation between the initial quark chemical potential (also initial temperature) and the rapidity, with increasing the rapidity the initial quark chemical potential goes up but the initial temperature goes down, thus initial antiquark number decreases to lead to the suppression of the dilepton production drastically. Thus, with increasing the rapidity the suppression of the dilepton production is an obvious characteristic indicating the formation of the QGM. At medium invariant massess the background is mainly from Drell-Yan mechanism, therefore, our results including this effect may be directly compared with future experiments at Brookhaven and CERN.

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