Incident energy dependence of dilepton production in an expanding baryon–rich quark–gluon fireball*

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Abstract From the full stopping scenario, the dilepton production in the baryon-rich quark-gluon fireball based on a relativistic hydrodynamic model is studied, and it is found that with increasing incident energy a characteristic plateau indicating the formation of the baryon-rich quark-gluon matter appears in the total yield.

Keywords Relativistic heavy-ion collisions, Hydrodynamic equation, Signature of quark–gluon plasma

Lattice quantum chromodynamics calculations exhibit a transition from normal nuclear matter to quark-gluon matter (QGM). Among all observables for the QGM formation, the dilepton is considered most promising because it does not suffer strong final-state interactions, and is therefore expected to retain information about the QGM.

Previous authors have studied the dilepton production for the baryon-free QGM.[1,2] Recent experiments and theories indicate that up to CERN SPS energies a sizable amount of baryon stopping occurs.[3] Even at RHIC bombarding energies $\sqrt{S} \leq 200A$ GeV calculations using microscopic models[3,4] hint that the colliding heavy ions may not be fully transparent. Thus, the dilepton production also depends on the baryon density. Dumitru *et al.*[3] have studied the dilepton production for given energy density at a finite baryon chemical potential. And Ko *et al.*[5] have also studied the dilepton production for baryon-rich QGM via a hydrodynamic description of heavy-ion collisions, in which the spatial average of the hydrodynamic equations has been taken. In this work, we study the incident energy dependence of the dilepton production in the baryon-rich QGM based on a relativistic hydrodynamic model.

For the quark phase, an expression of the dilepton production rate, dR/d^4P, was recently given on the basis of the Fermi–Dirac distribution function of quarks.[3] From this we have obtained the dilepton production spectrum dN/d^4XdM by an appropriate change of variables. For the hadronic phase, the dilepton production spectrum is calculated as in Refs.[2,6,7] using the momentum distribution function $f(p)=nc\ \exp(-E/T)$, where c is the normalization factor, n the particle density. Subsequently, the dilepton spectrum of the system is obtained via integrating the production spectra of the quark phase and the hadronic phase over the history of the spherical system according to its evolution.

We use the relativistic hydrodynamic equation (RHE) given in Refs.[6,8] to describe the evolution of the baryon-rich QGM fireball. To solve RHE, we should first find the equation of state (EOS) of the system. Following Refs.[6,8], 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.[9,10] In this work, following Ref.[9] we con-

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sider 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 which baryons in the quark phase become those in the hadronic phase. Thus, the phase transition can be described by a relaxation equation[11,12]

$$\frac{\mathrm{d}n_{\mathrm{b}}^{\mathrm{q}}(t)}{\mathrm{d}t}=-\frac{1}{\tau_{\mathrm{intr}}(t)}[n_{\mathrm{b}}^{\mathrm{q}}(t)-\bar{n}_{\mathrm{b}}^{\mathrm{q}}] \tag{1}$$

where $\bar{n}_{\mathrm{b}}^{\mathrm{q}}$ is the equilibrium baryon density value given by the Fermi distribution, $n_{\mathrm{b}}^{\mathrm{q}}(t)$ the baryon density of the quark phase. Taking $n_{\mathrm{b}}^{\mathrm{h}}(t)$ as the baryon density of the hadronic phase, $n_{\mathrm{b}}=n_{\mathrm{b}}^{\mathrm{q}}+n_{\mathrm{b}}^{\mathrm{h}}$ is the total baryon density in the transition region (i.e. mixed phase). The volume ratios of the quark phase and the hadronic phase in the transition region are, respectively, $\alpha_{\mathrm{q}}=n_{\mathrm{b}}^{\mathrm{q}}/n_{\mathrm{b}}$ and $\alpha_{\mathrm{h}}=(1-\alpha_{\mathrm{q}})$, from which the EOS of the transition region can be obtained. The intrinsic equilibration time has been estimated within a Fermi gas model [11,12], that is $\tau_{\mathrm{intr}}(t)=2\times10^{-22}$ s·MeV/$\varepsilon^{\star}(t)$, where $\varepsilon^{\star}$ is the excitation energy per baryon of the quark phase. From Eq.(1) the transition is described only through the change of the occupation $\bar{n}_{\mathrm{b}}^{q}$ of the baryon in the quark phase due to collisions from the residual interactions.[11]

According to the treatment of Ref.[5], for the central collision between two identical nuclei, the initial baryon density and energy density of the fireball are, respectively, $n_{\mathrm{b}}^{0}=2\gamma n_{0}$ and $e^{0}=\omega n_{\mathrm{b}}^{0}$, where γ and ω are, in turn, the Lorentz factor and center-of-mass energy per baryon, depending on the incident energy per baryon E_{in} [5], and n_0 the normal nuclear density. Employing the following relations from the standard bag model

$$n_{\mathrm{b}}^{0}=\frac{2}{3}\mu_{\mathrm{q}0}(T_0^2+\mu_{\mathrm{q}0}^2/\pi^2) \tag{2}$$

$$e^{0}=\frac{37}{30}\pi^2T_0^4+3T_0^2\mu_{\mathrm{q}0}+\frac{3}{2\pi^2}\mu_{\mathrm{q}0}^4+B \tag{3}$$

we can decide the initial temperature T_0 and quark chemical potential $\mu_{\mathrm{q}0}$ through the incident energy (see Fig.1), where B is the bag constant.

We first calculate the phase boundary for different bag constants as done in Ref.[8], then, using the EOS and initial values of the system solve the RHE in the $\mu_{\mathrm{b}}-T$ phase diagram to obtain the temperature and quark chemical potential distributions in the space-time, finally, calculate the dilepton spectrum from quark–anti-quark pair annihilations in the quark phase and from $\pi\pi$ annihilations in the hadronic phase. (see Fig.2)

Since here both the temperature and the quark chemical potential are functions of the space-time, compared with the system of the baryon-free QGM, it necessarily takes a long time for values (μ_{b},T) of various local regions of the fireball to reach different points of the phase boundary and to begin local phase transitions at different times. Such an effect of the phase boundary on the evolution delays the evolution process of the quark phase and hence significantly heightens the contribution of the quark phase to the production. Moreover, it makes the local phase transitions mostly occur at lower temperatures and higher quark chemical potentials. Even if the temperatures rise and quark chemical potentials decrease due to released latent heat, the temperatures of most local hadronized matter regions are still very low after the local phase transition. Thus, the contribution of the hadronic phase becomes so small that the spectra denoted by curves 2 to 9 in Fig.2 are without obvious humps at the invariant mass M=0.775 GeV. However, humps are clearly seen in the spectra given by previous authors.[1,2,5]

For a given incident energy, we can obtain an initial value $(\mu_{\mathrm{q}0},T_0)$ via solving Eqs.(2, 3). Thus, with increasing incident energy, the initial values $(\mu_{\mathrm{q}0},T_0)$ of the QGM fireball can be found in the phase diagram. As the same, considering the baryon density and energy density of the hadronic phase, employing Eqs.(2) and (3), the initial values of the hadronic matter fireball can be obtained, too. For the hadronic matter the effect of the temperature on the production dominates, thus, the dilepton production rapidly increases with incident energy as seen from curves 1 to 2 in Fig.2. However, for the QGM with increasing incident energy, on the one hand, the initial quark chemical potential the rises rapidly to cause the anti-quark density to decrease, thus, the production is suppressed. On the other hand, with the increase of the incident energy the volume of the initial system reduces, gradients of the temperature and baryon density between the outside and inside of the fireball increase and evolution accelerates, thus, the presence time of the QGM gets even shorter and the more energy of the system converts into the kinetic energy of the fluid to lead the production to be further suppressed. The results as seen in Fig.2 show that with increasing incident energy, once the QGM forms, the production no longer goes up obviously.

In order to further understand the relation between the dilepton production and the incident energy, we have calculated the total dilepton yield (N) as shown in Fig.3. It is shown that once the QGM creates the total yield shows a plateau.

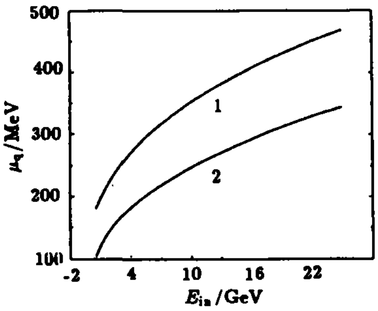

Fig.1 The relation between the incident energy and the initial temperature 1, and initial quark chemical potential 2 of the fireball formed from $^{197}A_u+^{197}A_u$ central collisions for $B^{1/4}$=0.30 GeV

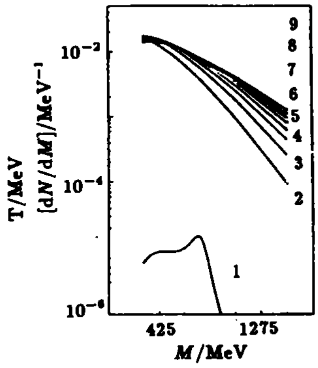

Fig.2 The dilepton spectra calculated in the phase diagram of the bag constant $B^{1/4}$=0.20 GeV. Curves 1 to 9 denote, in turn, the spectra for incident energies per nucleon E_{in}=1.00, 3.00, 5.00, 7.00, 9.00, 11.00, 13.00, 15.00 and 17.00 GeV

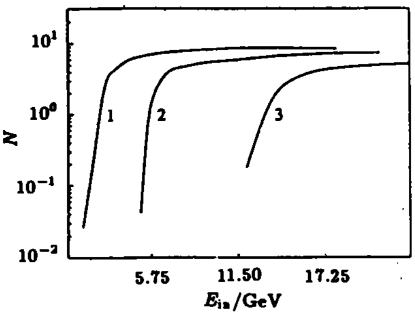

Fig.3 The total yield N vs the incident energy. Curves 1, 2 and 3 are, in turn, from the spectra shown in Fig.2 and from spectra obtained in the phase diagrams of $B^{1/4}$=0.25, 0.30 GeV

In conclusion, if baryon-rich QGM was created, due to the effect of the phase boundary on the evolution of the system the dilepton spectrum is without the hump of the contribution of the hadronic phase, in particular with increasing incident energy the total yield shows a plateau. Such an obvious characteristic for the baryon-rich QGM formation can be checked in future experiments at CERN and Brookhaven laboratory.

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