Rapid communication

Intermediate mass dilepton production in a chemically equilibrating quark-gluon matter

HE Ze-Jun[1,2], ZHANG Jia-Ju[2], LONG Jia-Li[2], JIANG Wei-Zhou[2]

([1]CCAST(World Laboratory) P.O. Box 8730,Beijing 100080; [2]Shanghai Institute of Nuclear Research, the Chinese Academy of Sciences, Shanghai 201800)

Abstract We find that in a chemically equilibrating baryon-rich quark-gluon matter, due to the slow cooling rate, high initial temperature, large gluon density as well as large fusion cross section of $gg \to c\bar{c}$ in the intermediate mass region, the gluon fusion $gg \to c\bar{c}$ provides a dominant contribution to dileptons with intermediate masses, resulting in the significant enhancement of intermediate mass dileptons.

Keywords Relativistic unclear collisions, Chemical non-equilibrium, Dileptons

CLC numbers O572.33, O572.31

High energy heavy-ion colliders RHIC and LHC will provide the best opportunity to study the formation of quark-gluon matter (QGM). Dileptons, as a signal for the QGM formation probably, are considered most promising because they do not suffer strong final interactions and are therefore expected to retain some information about the QGM. Previous authors[1,2] ,considering that the QGM is a thermodynamic equilibrium system (TES), studied the enhancement of dileptons with intermediate masses. In recent years, authors of Refs.[3,4] have indicated that due to large initial parton density in the QGM produced at RHIC energies, the partons suffer many collions in a very short time ($\tau \approx 0.3\text{–}0.7\,\text{fm}$), thus, the system may attain thermodynamic equilibrium. However, to achieve chemical equilibrium, more quarks and anti-quarks are needed, thus some energy is consumed, leading the system to cool faster. Such a system may be away from the chemical equilibrium. Authors of Refs.[5,6] have studied the chemical equilibration effect on the dilepton production in baryon-free QGM. In this paper, we describe the chemical equilibration effect on the dilepton production in the baryon-rich QGM, and calculate the thermal charmed quark contribution to dileptons with intermediate masses.

Following Refs.[6,7], we assume the dominant reactions leading to chemical equilibrium to be the processes $gg \leftrightarrow ggg$ and $gg \leftrightarrow q\bar{q}$, and the evolution of the parton density can be given by the master equations. For the baryon-rich QGM, according to the discussion in Ref.[6] we take the factorized Fermi-Dirac distribution function $f_{q(\bar{q})} = \lambda_{q(\bar{q})} \Big/ (\mathrm{e}^{(p \mp \mu)/T} + 1)$ for quarks and factorized Bose-Einstein distribution function $f_g(p) = \lambda_g \Big/ (\mathrm{e}^{p/T} - 1)$ for gluons. Considering that taking $\lambda_q = \lambda_{\bar{q}}$ does not change the qualitative property of the evolution of the chemically equilibrating baryon-rich system (CES), combining the master equations together with equation of the conservation of energy-momentum and equation of the conservation of baryon number, one can get a set of coupled relaxation equations describing evolutions of the temperature T, quark chemical potential μ_q and fugacities λ_q for quarks and λ_g for gluons.

As is well known, for the quark phase, dilepton yield is given by

$$\frac{\mathrm{d}R}{\mathrm{d}^4 p} = \int \frac{\mathrm{d}^3 p_1}{(2\pi)^3} \frac{\mathrm{d}^3 p_2}{(2\pi)^3} \gamma_q f_q(p_1) f_{\bar{q}}(p_2) U_{q\bar{q}} \sigma_{q\bar{q}}^{l\bar{l}} \delta^4(p - p_1 - p_2) \tag{1}$$

where $R=\mathrm{d}N/\mathrm{d}x^4$ is the total number of lepton pairs emitted per unit space-time, $U_{q\bar{q}}$ the relative velocity between the quark and anti-quark, $\sigma_{q\bar{q}}^{l\bar{l}}$ the cross section for the reaction $q\bar{q} \to l\bar{l}$, γ_q the degeneracy factor of the

Supported in part by CAS Knowledge Innovation Project No.KJCX2-N11, the National Natural Science Foundation of China No.10075071 and No.19975053, the Major State Basic Research Development Program in China under Contract No. G200077400 and CAS Knowledge Innovation Project

Received date: 2002-10-24

reaction system $q\bar{q}$. Taking the factorized Fermi-Dirac distribution function of quarks as mentioned above, from the view point of experiment, for the longitudinal scaling expansion, with the help of Ref.[2], we obtain dilepton yield from $q\bar{q} \to l\bar{l}$ annihilations in the CES

$$\frac{\mathrm{d}N}{\mathrm{d}M^2\mathrm{d}Y} = \frac{\alpha^2 R^2}{2\pi^2} F_q \int \mathrm{d}M_T^2 \mathrm{d}\tau \tau \lambda_q^2 \sqrt{\frac{2\pi T}{M_T}} \exp[-\frac{M_T}{T}] J_q(T, M, \mu_q) \tag{2}$$

where Y, M and M_T are, in turn, the rapidity, invariant mass and transverse mass of the dilepton, Fq the form factor of the quark, and πR^2 the transverse area of the QGM. The factor $J_q(T, M, \mu_q)$ is related to the temperature, dilepton invariant mass and quark chemical potential.

With a large initial temperature in the most optimistic scenario, $T_{i,\max} \approx (\frac{1}{3} - \frac{1}{2}) m_c$, significant thermal charm production may be expected,[8] where m_c is the mass of the charmed quark. For the CES, produced in collisions at RHIC energies, with very high initial temperature (～0.57 GeV) evaluated by the Hijing model,[9] thermal charmed quark production and its contribution to lepton pair should be included. We consider only charmed quark production through the gluon fusion $gg \to c\bar{c}$ and quark fusion $q\bar{q} \to c\bar{c}$. In Refs.[9,10], the charmed quark production cross section has been given by $\sigma_{c\bar{c}}(M) = \gamma_q \sigma_{q\bar{q}\to c\bar{c}}(M) + \gamma_g \sigma_{gg\to c\bar{c}}(M)$, where $\sigma_{q\bar{q}\to c\bar{c}}$ and $\sigma_{gg\to c\bar{c}}$ are, respectively, cross sections for $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$ reactions in leading–order QCD, which have been given;[9,10] the degeneracy factors for thermal quark and gluon reaction systems are, respectively, $\gamma_q = N_f (2\times3)^2$ and $\gamma_g = (2\times8)/2$. Replacing $\gamma_g f_q(p_1) f_{\bar{q}}(p_2) U_{q\bar{q}} \sigma_{q\bar{q}}^{l\bar{l}}$ in the reaction rate expression by $\gamma_g f_g(p_1) f_g(p_2) U_{gg} \sigma_{gg\to c\bar{c}}(M)$ and $\gamma_g f_q(p_1) f_{\bar{q}}(p_2) U_{q\bar{q}} \sigma_{q\bar{q}\to c\bar{c}}(M)$, we have obtained the charmed quark production, where U_{gg} is the relative velocity between gluons, $f_q(p)$ and $f_g(p)$ are, respectively, the factorized distribution functions of quarks and gluons, again. Almost all of the produced charmed quarks would eventually hadronize to D-mesons.[9] We also neglect charm fragmentation as done in Refs.[9,10]. Considering that the D-meson decays to leptons with a 34% branching ratio (or either a μ or an e) for charged D-mesons, or a 15% branching ratio for neutral D-mesons,[9] finally one can get the contribution of the charm production from reactions $q\bar{q} \to c\bar{c}$ and $gg \to c\bar{c}$ to lepton pairs.

For ^{197}Au+^{197}Au central collisions at RHIC energies, taking initial values τ_0 =0.20 fm, $T_0 = 0.57$ GeV, $\lambda_{g0} = 0.09$ and $\lambda_{q0} = 0.02$ of the CES according to Hijing model calculation,[6] solving the set of coupled relaxation equations, we have obtained the temperature distribution. Curves 1 and 2 in Fig.1 represent, in turn, the calculated temperature distributions for initial quark chemical potentials $\mu_{q0} = 0.10$ and 0.86 GeV. One has known that the baryon-free QGM converts into the hadronic matter only with decreasing the temperature along the temperature axis of the phase diagram, and the phase transition occurs at a certain critical temperature T_c. However, in this work, both the quark chemical potential and the temperature of the CES are functions of time, compared with the baryon-free QGM it necessarily takes a long time for value (μ_q, T) of the system to reach a certain point of the phase boundary to make a phase transition. Such an effect will delay the evolution process of the CES, thus the cooling of the CES slows down. On the other hand, with increasing the initial quark chemical potential, initial quarks increase, causing more collisions of quarks, thus the quark equilibration rate goes up, while the calculation shows that the quark production rate R_2 is suppressed, making the quark equilibration rate going down. The whole effect makes the quark equilibration rate somewhat going up. However, the calculation also shows that with increasing the initial quark chemical potential the suppression of the production rate R_3 of gluons is much stronger than the one of the R_2 of quarks, so that the gluon (included mostly in the CES) equilibration rate slows down, energy loss of the system decreases and cooling rate of the system goes down. Therefore, the temperature curve 2 obtained at a higher initial quark chemical potential μ_{q0} is above the temperature curve 1 obtained at a lower value μ_{q0} as seen in Fig.1.

The calculated dilepton yields dN/dM^2dY are shown in Fig.2. Dashed lines 1 and 2 are, in turn, calculated yields from the quark annihilation $q\bar{q} \to l\bar{l}$ and the gluon fusion $gg \to c\bar{c}$ in the TES at CERN-SPS energies. In this case, the contribution of $q\bar{q} \to l\bar{l}$ still dominates. As mentioned in above section, with increasing the initial quark chemical potential μ_{q0} the cooling of the CES slows down, the lifetime of the quark phase increases, accordingly the contribution of the quark phase goes up. Adding the very high initial temperature of the CES produced at RHIC energies, the enhancement of dileptons becomes even more obvious. Especially, the yield of $gg \to c\bar{c}$ strongly depends on the initial temperature of the QGM system, moreover $gg \to c\bar{c}$ has very large cross section in the intermediate mass region[9] .Therefore, in Fig.2 one can see that the enhancement of dileptons with intermediate masses is mainly due to the contribution of the gluon fusion $gg \to c\bar{c}$, i.e. the contribution of $gg \to c\bar{c}$ (curve 5) is above that of $q\bar{q} \to l\bar{l}$ (curve 4). The curve 3 is the contribution of $q\bar{q} \to c\bar{c}$.

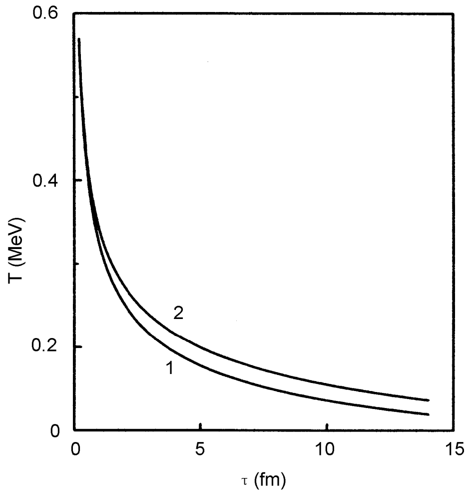

Fig.1 The calculated temperature distributions for initial values $\tau_0 = 0.20\,\text{fm}$, T_0=0.57 GeV, $\lambda_{g0} = 0.09$ and $\lambda_{q0} = 0.02$. Curves 1 and 2 are, in turn, the distributions at initial quark chemical potentials $\mu_{q0} = 0.10$ and 0.86 GeV.

In conclusion, in a chemically equilibrating baryon-rich quark-gluon matter, due to slow cooling rate caused by the effect of the hydrodynamical evolution of the CES with the finite baryon density, high initial temperature, large gluon density as well as large fusion cross section of $gg \to c\bar{c}$ in the intermediate mass region, the fusion $gg \to c\bar{c}$ provides a dominant contribution to dileptons with intermediate masses, making a significant enhancement of intermediate mass dielptons. Such an enhancement may be a signal for the QGM formation in collisions at RHIC energies.

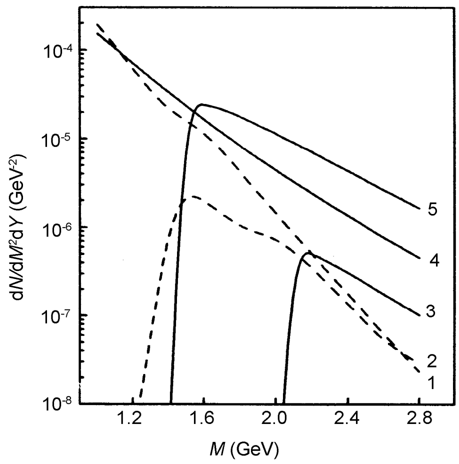

Fig.2 The calculated dilepton yields dN/dM^2dY. Dashed lines 1 and 2 are, in turn, calculated yields from reactions $q\bar{q}$ annihilation and $gg \to c\bar{c}$ in TES at CERN-SPS energies. Curves 3-5 are, in turn, calculated yields from $q\bar{q} \to c\bar{c}$, $q\bar{q}$ annihilations and $gg \to c\bar{c}$ in the CES under the same initial conditions as given in Fig.1.

References

1 Li G Q, Gale C. Phys Rev, 1998, C**58**: 2914

2 He Z J, Zhou W J, Jiang W Z *et al.* Phys Lett, 2000, B**495**: 317

3 Shuryak E. Phys Rev Lett, 1992, **68**: 3270

4 Eskola K J, Wang X N. Phys Rev, 1994, D**49**: 1284

5 Shuryak E, Xiong L. Phys Rev Lett, 1993,**70**: 2241

6 Biró T S, Doorn E V, Müller B *et al.* Phys Rev, 1993, C**48**: 1275

7 Levai P, Müller B, Wang X N. Phys Rev, 1995, C**51**: 3326

8 Kämpfer B, Pavlenko OO P, Gorenstein M I *et al.* Z Phys, 1995, A**353**: 71

9 Shor A. Phys Lett, 1988, B**215**: 375; Phys Lett, 1989, B**233**: 231

10 Combridge B L. Nucl Phys, 1979, B**151**: 429

11 Kostyuk A P, Gorenstein M I, Greiner W. Phys Lett, 2001, B**519**: 207