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The shear viscosity of a chemically equilibrating quark-gluon plasma at finite baryon density

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Abstract – Taking account of elastic $gg \to gg$ and bremsstrahlung $gg \leftrightarrow ggg$ processes, as well as quark elastic scattering, we calculated the shear viscous coefficient of a chemically equilibrating quark-gluon plasma at finite baryon density. We found that the inelastic bremsstrahlung processes make the shear viscosity remarkably lower, and the ratio of shear viscosity to entropy density η/s increases with increasing initial quark chemical potential. Considering the effect of shear viscosity the evolution of the QGP system was investigated. We found that the evolution of the system becomes slower owing to viscosity compared to the one in the ideal case, and the inelastic bremsstrahlung processes make the slower rate of the system not as much as in our previous calculations.

Introduction. – The Relativistic Heavy-Ion Collider (RHIC) at the Brookhaven National Laboratory and the Large Hadron Collider (LHC) at CERN have provided the best opportunity to study the formation and evolution of Quark-Gluon Plasma (QGP). The experimental results accumulated in the last decade have shown that the strongly coupled QGP has been created and behaves like an almost perfect liquid. The transport properties of the QGP have attracted a lot of attention and are a currently hot topic.

Viscous hydrodynamics is a good model to study the viscosity and its effect on the formation and evolution of QGP. The viscous coefficient in the framework of hydrodynamics is composed of bulk and shear viscosity, while the bulk viscosity can be neglected for a quark-gluon plasma [1]. The authors of [1] have studied the viscous corrections to the hydrodynamic equations describing the evolution of the QGP at finite baryon density, and investigated the effect of viscosity on the chemical equilibration of the system. They have found that, due to the viscosity, the lifetime of the plasma increases, the temperature evolution of the system becomes slow, and the chemical equilibration of the system becomes fast, therefore, the reaction rate will be raised.

Shuryak and co-workers [2,3] indicated that if the system achieves chemical equilibrium, more quarks and antiquarks are needed, thus some energy is consumed, leading to the faster cooling of the system; therefore, such a system is away from the chemical equilibrium. Hammon and co-workers [4,5] have calculated the initial conditions of the non-equilibrium QGP produced at RHIC energies and indicated that the initial system has finite baryon density. In our work [6], we mainly discuss shear viscosity and its effect on a chemically equilibrating quark-gluon plasma at finite baryon density.

In the viscous hydrodynamics the viscous coefficient is mostly regarded as an adjustable parameter [1,7–9]. Whereas, in the kinetic transport theory, shear viscosity can be extracted from microscopic transport calculations. Many authors have done a lot of work to give evaluation formulas of viscous coefficients using various treatments. The authors of [10] have derived shear viscosity based on QCD phenomenology for a baryon-free plasma and the authors of [11] considered Debye screening and the damping rate of gluons for a baryon-rich plasma using finite-temperature QCD. In ref. [12], shear viscosity was estimated by considering the Landau damping effect. The authors of [13,14] have successively derived leading-log and full leading-order calculations of shear viscosity in weakly coupled high-temperature gauge theories. Recently, Chen and co-workers studied the leading-log order viscosities of a weakly coupled QGP with finite temperature and quark chemical potential [15].

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In our previous work [6], we have calculated shear viscosity using the formula given by the relativistic kinetic theory for a massless QGP under relaxation time approximation in a chemically equilibrating quark-gluon plasma at finite baryon density. The parton reactions we considered include quark and gluon elastic scattering only. The authors of [14,16–23] have calculated shear viscosity for gluon gas in kinetic theory including elastic $gg\rightarrow gg$ and inelastic bremsstrahlung $gg\leftrightarrow ggg$ processes by using different approaches. Xu *et al.* [16–22] found that the contribution of $gg\leftrightarrow ggg$ is more important to shear viscosity than $gg\rightarrow gg$. In this work, we will extend our previous work [6] to include the gluon bremsstrahlung processes to recalculate the shear viscous coefficient, and investigate its effect on the evolution of the chemically equilibrating QGP at finite baryon density.

The paper is organized as follows. The second section provides the evolution of the dissipative QGP system. In the third section we present calculation and discussion. Finally we give a brief summary and conclusion in the fourth section.

Evolution of the dissipative QGP system. – In this work, we describe the distribution functions of partons with Jüttner distributions $f_{q(\bar{q})} = \lambda_{q(\bar{q})}/(e^{(p\mp\mu_q)/T} + \lambda_{q(\bar{q})})$ for quarks (antiquarks) and $f_g = \lambda_g/(e^{p/T} - \lambda_g)$ for gluons, where fugacity λ_i (≤ 1) of the parton of type i is used to characterize the non-equilibrium of the system. Based on these distribution functions, we first derive the thermodynamic relations of the chemically equilibrating QGP system at finite baryon density. Expanding densities of quarks (antiquarks)

$$n_{q(\bar{q})} = \frac{g_{q(\bar{q})}}{2\pi^2}\lambda_{q(\bar{q})}\int \frac{p^2\mathrm{d}p}{\lambda_{q(\bar{q})} + e(p\mp\mu_q)/T} \tag{1}$$

over the quark chemical potential μ_q, we get the baryon density of the system [6,24],

$$\begin{aligned} n_{b,q} = \frac{g_q}{6\pi^2}\Bigg[&T^3(Q_1^2\lambda_q - \bar{Q}_1^2\lambda_{\bar{q}}) \\ &+ 2\mu_q T^2(Q_1^1\lambda_q + \bar{Q}_1^1\lambda_{\bar{q}}) + T\mu_q^2(Q_1^0\lambda_q - \bar{Q}_1^0\lambda_{\bar{q}}) \\ &+ \frac{1}{3}\mu_q^3\left(\frac{\lambda_q}{\lambda_q+1} + \frac{\lambda_{\bar{q}}}{\lambda_{\bar{q}}+1}\right)\Bigg], \end{aligned} \tag{2}$$

and the corresponding energy density

$$\begin{aligned} \epsilon_{QGP} = \frac{g_q}{2\pi^2}\Bigg[&T^4(Q_1^3\lambda_q + \bar{Q}_1^3\lambda_{\bar{q}}) \\ &+ 3\mu_q T^3(Q_1^2\lambda_q - \bar{Q}_1^2\lambda_{\bar{q}}) + 3\mu_q^2 T^2(Q_1^1\lambda_q + \bar{Q}_1^1\lambda_{\bar{q}}) \\ &+ T\mu_q^3(Q_1^0\lambda_q - \bar{Q}_1^0\lambda_{\bar{q}}) + \frac{1}{4}\mu_q^4\left(\frac{\lambda_q}{\lambda_q+1} + \frac{\lambda_{\bar{q}}}{\lambda_{\bar{q}}+1}\right) \\ &+ \frac{g_g}{g_q}T^4 G_1^3\lambda_g + \frac{2\pi^2 B_0}{g_q}\Bigg], \end{aligned} \tag{3}$$

where $g_{q(\bar{q})}$ and g_g are degeneracy factors of quarks (antiquarks) and gluons, respectively. Since the convergence of the following integral factors appearing in the expansion above:

$$\begin{aligned} G_m^n &= \int \frac{Z^n\mathrm{d}Z}{(e^Z - \lambda_g)^m}, \\ Q_m^n &= \int \frac{Z^n\mathrm{d}Z}{(e^Z + \lambda_q)^m}, \\ \bar{Q}_m^n &= \int \frac{Z^n\mathrm{d}Z}{(e^Z + \lambda_{\bar{q}})^m}, \end{aligned} \tag{4}$$

is very rapid, it is easy to calculate these integral numerically [6,24].

We consider the reactions leading to chemical equilibrium: $gg\leftrightarrow ggg$ and $gg\leftrightarrow q\bar{q}$. Assuming that elastic parton scatterings are sufficiently rapid to maintain local thermal equilibrium, the evolutions of gluon and quark densities can be given by the master equations, respectively. We first extend the master equations to include the viscosity as done in [1]. Similarly, the evolution of the baryon density can be described by a corrected conservation equation of the baryon number including a viscous term. In addition, due to viscosity, a viscous term would be contained in the conservation equation of the energy-momentum, too. Combining the master equations together with the equation of the baryon number conservation and the equation of the energy-momentum conservation including viscous corrections, for the longitudinal scaling expansion of the system, one can get a set of Coupled Relaxation Equations (CRE) describing evolutions of the temperature T, quark chemical potential μ_q, and fugacities λ_q for quarks and λ_g for gluons on the basis of the thermodynamic relations of the chemically equilibrating QGP system at finite baryon density [1,6,24],

$$\begin{aligned} &\left(\frac{1}{\lambda_g} + \frac{G_2^2}{G_1^2}\right)\dot{\lambda}_g + 3\frac{\dot{T}}{T} + \frac{1}{\tau} = R_3\left[1 - \frac{G_1^2}{2\xi(3)}\lambda_g\right] \\ &-2R_2\left[1 - \left(\frac{2\xi(3)}{G_1^2}\right)^2\frac{n_g n_{\bar{q}}}{\bar{n}_g\bar{n}_{\bar{q}}}\frac{1}{\lambda_g^2}\right] + \frac{\eta}{\epsilon\tau^2}, \end{aligned} \tag{5}$$

$$\begin{aligned} &\dot{\lambda}_q\Bigg[T^3(Q_1^2 - \lambda_q Q_2^2) + 2\mu_q T^2(Q_1^1 - \lambda_q Q_2^1) \\ &+ T\mu_q^2(Q_1^0 - \lambda_q Q_2^0) + \frac{1}{3}\mu_q^3\frac{1}{(\lambda_q+1)^2}\Bigg] \\ &+ \dot{T}[3\lambda_q T^2 Q_1^2 + 4\lambda_q\mu_q T Q_1^1 + \lambda_q\mu_q^2 Q_1^0] \\ &+ \dot{\mu_q}\left[2\lambda_q T^2 Q_1^1 + 2\lambda_q\mu_q T Q_1^0 + \mu_q^2\frac{\lambda_q}{\lambda_q+1}\right] + \frac{n_q^0}{\tau} = \\ &n_g^0 R_2\left[1 - \left(\frac{2\xi(3)}{G_1^2}\right)^2\frac{1}{\lambda_g^2}\frac{n_g n_{\bar{q}}}{\bar{n}_g\bar{n}_{\bar{q}}}\frac{1}{\lambda_g^2}\right] + \frac{\eta n_q^0}{\epsilon\tau^2}, \end{aligned} \tag{6}$$

$$\begin{aligned} &\dot{\lambda}_q\left[2T^2\mu_q(Q_1^1 - \lambda_q Q_2^1) + \frac{1}{3}\mu_q^3\frac{1}{(\lambda_q+1)^2}\right] \\ &+ \dot{T}4\lambda_q\mu_q T Q_1^1 + \dot{\mu_q}\left[2\lambda_q T^2 Q_1^1 + \mu_q^2\frac{\lambda_q}{\lambda_q+1}\right] = \\ &-\frac{1}{\tau}\left[2T^2\mu_q Q_1^1\lambda_q + \frac{1}{3}\mu_q^3\frac{\lambda_q}{\lambda_q+1}\right] + \frac{6\pi^2}{g_q}\frac{\eta n_b}{\epsilon\tau^2}, \end{aligned} \tag{7}$$

$$\dot{\lambda}_g \frac{g_g}{g_q} T^4 (G_1^3 + \lambda_g G_2^3) + \dot{\lambda}_q \Big[2T^4 (Q_1^3 - \lambda_q Q_2^3) + 6T^2 \mu_q^2 (Q_1^1 - \lambda_q Q_2^1) + \frac{1}{2} \mu_q^4 \frac{1}{(\lambda_q + 1)^2} \Big] + \dot{T} \Big[8\lambda_q T^3 Q_1^3 + 12 \lambda_q \mu_q^2 T Q_1^1 + 4 \frac{g_g}{g_q} \lambda_g T^3 G_1^3 \Big] + \dot{\mu_q} \Big[12 \mu_q \lambda_T T^2 Q_1^1 + 2\mu_q^3 \frac{\lambda_q}{\lambda_q + 1} \Big] = - \frac{4}{3\tau} \Big[2T^4 Q_1^3 \lambda_q + 6T^2 \mu_q^2 \lambda_q Q_1^1 + \frac{\mu_q^4}{2} \frac{\lambda_q}{\lambda_q + 1} + \frac{g_g}{g_q} \lambda_q T^4 G_1^3 \Big] + \frac{4}{3} \frac{2\pi^2}{g_q} \frac{\eta}{\tau^2}, \tag{8}$$

where $\bar{n}_{q(\bar{q})}$ is the value of $n_{q(\bar{q})}$ at $\lambda_{q(\bar{q})} = 1$, $n_q^0 = n_q/(g_q/2\pi^2)$, $n_g^0 = n_g/(g_g/2\pi^2)$, $\xi(3) = 1.20206$, and η the shear viscous coefficient. The gluon and quark production rates R_3/T and R_2/T are, respectively, given by [6,24–27].

The viscous coefficient η in our work is calculated according to [10,28,29]. Using the relativistic kinetic theory for a massless QGP in the relaxation time approximation the shear viscous coefficient is written as

$$\eta_i = \frac{4}{15} \epsilon_i \lambda_i, \tag{9}$$

where λ_i is the mean free path of the particle of type i in QGP, as the inverse of interaction rate R_i. Taking isotropic approximation, in a chemically equilibrating QGP for quark scattering R_i is given by

$$R_q = \frac{4n_q}{9} 2\pi {\alpha_s}^2 \frac{9T^2/2}{M_D^2(M_D^2 + 9T^2/2)}, \tag{10}$$

for gluon scattering $gg \to gg$ by

$$R_g = \frac{9n_g}{4} 2\pi {\alpha_s}^2 \frac{9T^2/2}{M_D^2(M_D^2 + 9T^2/2)}. \tag{11}$$

Following ref. [27], taking into account the LPM effect, the differential cross-section for the process $gg \to ggg$ is

$$\frac{d\sigma_3}{\mathrm{d}q_\perp^2 \,\mathrm{d}y d^2 k_\perp} = \frac{\mathrm{d}\sigma_{el}^{gg}}{\mathrm{d}q_\perp^2} \frac{\mathrm{d}n_g}{\mathrm{d}y \mathrm{d}^2 k_\perp} \times \theta(\lambda_f - \tau_{QCD}) \theta(\sqrt{18T^2} - k_\perp \cosh y), \tag{12}$$

where the λ_f is the mean free path and τ_{QCD} is the effective formation time of the gluon radiation in QCD. The regularized gluon density distribution induced by a single scattering given by Gunion and Bertsch [30] is

$$\frac{\mathrm{d}n_g}{\mathrm{d}y \mathrm{d}^2 k_\perp} = \frac{3\alpha_s}{\pi^2} \frac{q_\perp^2}{k_\perp^2 [(\mathbf{k}_\perp - \mathbf{q}_\perp)^2 + M_D^2]}. \tag{13}$$

Substituting the gg scattering cross and the mean free path for elastic scattering, doing part of the integrations we can obtain the rate for the process $gg \to ggg$,

$$R_{23}/T = \frac{32}{3a_1} \frac{\alpha_s}{\lambda_g} \left[\frac{(M_D^2 + s/4) M_D^2}{9g^2 T^4/2} \right]^2 I(\lambda_g, \lambda_q, T, \mu_q), \tag{14}$$

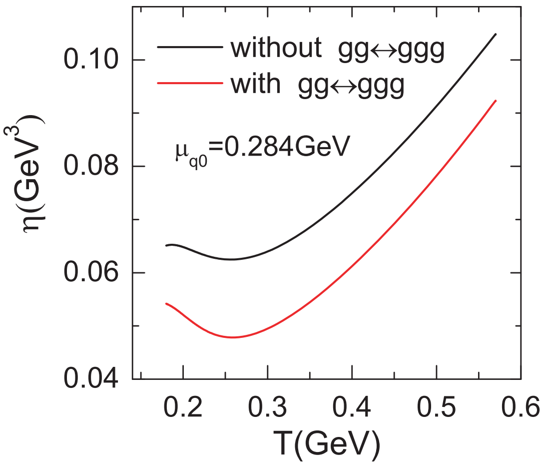

Fig. 1: (Colour on-line) The viscous coefficient η as a function of the temperature for initial quark chemical potential $\mu_{q0} = 0.284\,\text{GeV}$. Black and red lines denote, respectively, the calculated viscous coefficients η without or with considering the inelastic bremsstrahlung $gg \leftrightarrow ggg$ processes.

and for $ggg \to gg$ we take $R_{32} = 2/3 R_{23}$ [16–18], where M_D^2 is the Debye screening mass, and $I(\lambda_g, \lambda_q, T, \mu_q)$ is the function of λ_g, λ_q, T, μ_q [6,27]. Thus, we can directly calculate the viscous coefficients η_q, η_g and their total η from the thermodynamic quantities of the QGP system.

Calculations and Discussion. – In this work, we focus on discussing $\text{Au}^{197} + \text{Au}^{197}$ central collisions at the RHIC energies. With the help of [31,32] we take the initial values of the system: $\tau_0 = 0.70\,\text{fm}$, $T_0 = 0.570\,\text{GeV}$, $\lambda_{g0} = 0.08$ and $\lambda_{q0} = 0.02$. We have investigated the shear viscous coefficient and its effect on the evolution of the system. Especially, we have studied the effect of inelastic bremsstrahlung $gg \leftrightarrow ggg$ processes. To understand the effect of the baryon density on the system evolution, we have solved the CRE for initial quark chemical potentials $\mu_{q0} = 0.001$, 0.284, 0.568, and $0.852\,\text{GeV}$, and obtained the evolutions of the temperature T, quark chemical potential μ_q and fugacities λ_g and λ_q, and the shear viscosity of the system.

In fig. 1 we have shown the viscous coefficient η as a function of the temperature for initial quark chemical potentials $\mu_{q0} = 0.284\,\text{GeV}$. Black and red lines denote, respectively, the calculated viscous coefficients η without or with considering the inelastic bremsstrahlung $gg \leftrightarrow ggg$ processes. From fig. 1, one can see that the shear viscosity η increases with increasing the temperature T, which is in accordance with the previous conclusion, and the inelastic bremsstrahlung processes significantly lower the shear viscosity by a factor of almost one-fifth.

The temperature dependence of the ratio of shear viscosity to entropy density η/s is given in fig. 2. Black, red, green and blue curves denote, in turn, the calculated ratio for the initial quark chemical potentials $\mu_{q0} = 0.001$, 0.284, 0.568, and $0.852\,\text{GeV}$, where the solid and dashed

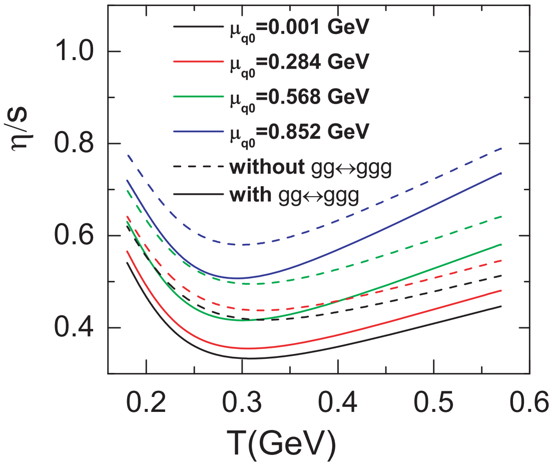

Fig. 2: (Colour on-line) The ratio of shear viscosity to entropy density η/s as a function of the temperature. Black, red, green and blue curves denote, in turn, the calculated ratio η/s for initial quark chemical potentials $\mu_{q0} = 0.001$, 0.284, 0.568, and 0.852 GeV, where the solid and dashed lines denote, respectively, the cases including or not the inelastic bremsstrahlung processes.

lines denote, respectively, the calculation including or not including the inelastic bremsstrahlung processes. From fig. 2, we see that the ratio η/s increases with increasing initial quark chemical potential. This result coincides with ref. [15], in which the authors found that the value of η/s is smallest at $\mu_q = 0$. And also from the figure one can clearly see that the inelastic bremsstrahlung processes bring the ratio down obviously to be closer to $1/4\pi$.

To present the effect of chemical non-equilibration, we calculated the shear viscosity of a chemical equilibrium system for comparison by setting fugacities $\lambda_{g,q} = 1$. The results are shown in fig. 3. The upper and lower panels show the shear viscosity η and the ratio of shear viscosity to entropy density η/s, respectively. The solid lines denote calculations in a chemically equilibrating system ($\lambda_{g,q} < 1$), and the dashed ones those in a chemical equilibrium system ($\lambda_{g,q} = 1$), where, in fig. 3(a), the dashed lines are shear viscosities divided by 10. Black and red lines have the same meaning as in fig. 1. From fig. 3, one can see that shear viscosity η and the ratio η/s are much lower for a chemically equilibrating system than those for a chemical equilibrium one. This can be attributable to the additional consumption of energy in a chemical non-equilibrium system, which has been revealed by refs. [2,3].

To understand the effect of shear viscosity on the evolution of the QGP system, we have solved the CRE of an ideal system and of a viscous one for comparison. Especially, in the case of a viscous system, we investigated the effect of inelastic bremsstrahlung processes. Figure 4 shows the evolution of the shear viscosity η with proper time τ at initial quark potential $\mu_{q0} = 0.284$ GeV. The black and red curves denote, respectively, the calculated viscosity without or with considering the inelastic bremsstrahlung processes. From fig. 4 we see that the shear viscous coefficient first declines sharply with proper time and then rises slowly. In addition, the inelastic bremsstrahlung processes significantly lower the shear viscosity as stated before.

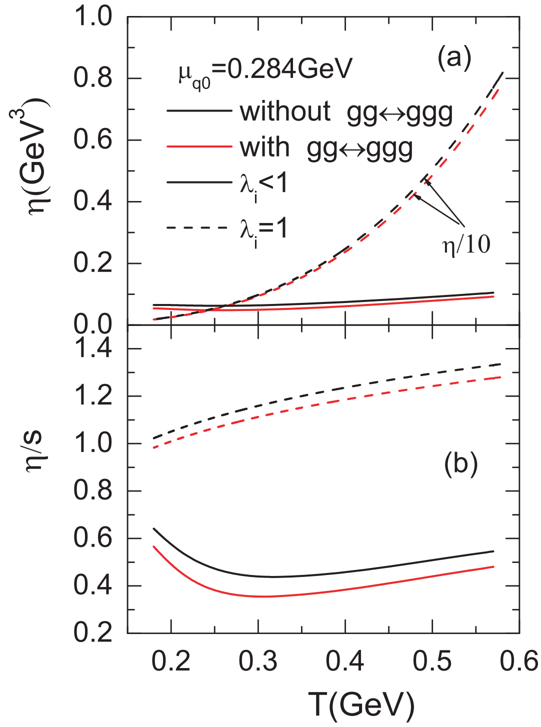

Fig. 3: (Colour on-line) The shear viscosity η (a) and ratio of shear viscosity to entropy density η/s (b) for the chemical equilibrium and non-equilibrium QGP system. The solid lines denote calculations in the chemically equilibrating system ($\lambda_{g,q} < 1$), and the dashed ones those in the chemical equilibrium system ($\lambda_{g,q} = 1$), where, in (a), the dashed lines are shear viscosities divided by 10. Black and red lines have the same meaning as in fig. 1.

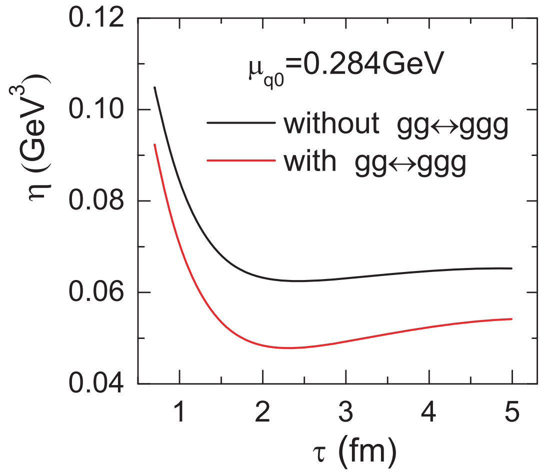

Fig. 4: (Colour on-line) The evolutions of the shear viscosity η with proper time τ at initial quark potential $\mu_{q0} = 0.284$ GeV. The black and red curves denote, respectively, the calculated viscosity without or with considering the inelastic bremsstrahlung processes.

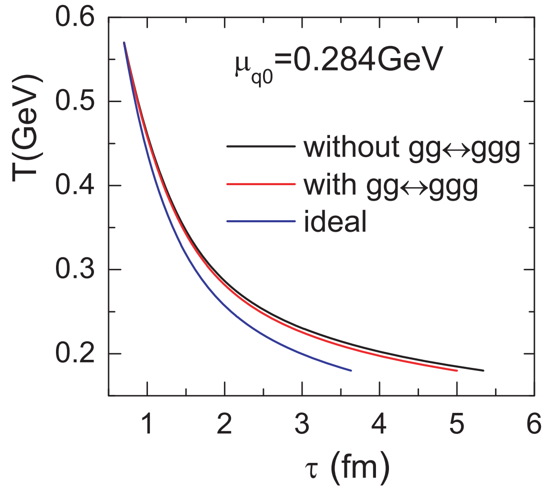

Fig. 5: (Colour on-line) The evolutions of the temperature T with proper time τ for an ideal and a viscous system at initial quark potential $\mu_{q0} = 0.284\,\mathrm{GeV}$. The black and red curves denote, respectively, the calculated viscosity without or with considering the inelastic bremsstrahlung processes, and the blue one denotes the case of the ideal system.

The evolution of the temperature T with proper time τ is given by fig. 5, for the ideal and the viscous systems at initial quark potential $\mu_{q0} = 0.284\,\mathrm{GeV}$. The black and red curves denote, respectively, the calculated viscosity without or with considering the inelastic bremsstrahlung processes, and the blue one denotes the case of the ideal system. From fig. 5 one can see that the evolution of the system becomes slower owing to viscosity compared to the one in the ideal case, which means that the viscosity makes the lifetime of the QGP system increase. However, due to the inelastic bremsstrahlung processes making the shear viscosity lower, the slower rate of the system is not as much as in our previous calculations when the inelastic bremsstrahlung processes are not considered. This can be explained by the fact that the speed of evolution of QGP system is inversely proportional to shear viscosity.

Summary and conclusion. – In this work, taking into account reactions $gg\leftrightarrow ggg$ and $gg\leftrightarrow q\bar{q}$ leading to the chemical equilibrium of the QGP system, conservations of energy-momentum and baryon number, as well as viscosity of the QGP system, we have derived a set of coupled CRE of the chemically equilibrating QGP system with viscosity at finite baryon density, produced from $\mathrm{Au}^{197} + \mathrm{Au}^{197}$ central collisions at RHIC energies, which describes the space-time evolution of the system. By using the shear viscous coefficient given by the relativistic kinetic theory for a massless QGP under relaxation time approximation, taking account of elastic $gg\rightarrow gg$ and bremsstrahlung $gg\leftrightarrow ggg$ processes, as well as quark elastic scattering, we have estimated the mean free paths of quarks and gluons in a chemically equilibrating QGP at finite baryon density, then combining with the parton energy densities, we calculated the shear viscous coefficient of the QGP. Then, we solved the CRE, and directly obtained the viscous coefficient from the thermodynamic quantities of the QGP system. We found that the inelastic bremsstrahlung processes make the shear viscosity remarkably lower. We have also calculated the ratio of shear viscosity to entropy density η/s, and found that the ratio increases with increasing initial quark chemical potential, and the inelastic bremsstrahlung processes bring the ratio obviously down. Subsequently, based on the calculated shear viscosity, we have investigated the effect of shear viscosity on the evolution of the QGP. We found that the evolution of the system becomes slower owing to viscosity compared to the one in the ideal case, and the inelastic bremsstrahlung processes make the slower rate of the system not as much as in our previous calculations, which can be interpreted as the inverse proportion of the speed of the evolution of QGP system to the shear viscosity.

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