Eur. Phys. J. C 50, 629–634 (2007)
DOI 10.1140/epjc/s10052-007-0233-7

THE EUROPEAN
PHYSICAL JOURNAL C

Regular Article – Theoretical Physics

Revisiting the quasi-particle model of the quark–gluon plasma

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Received: 27 August 2006 / Revised version: 12 January 2007 /
Published online: 21 February 2007 –

Abstract. The quasi-particle model of the quark–gluon plasma (QGP) is revisited here with a new method, different from earlier studies, one without the need of a temperature dependent bag constant and other effects such as confinement, effective degrees of freedom etc. Our model has only one system dependent parameter and shows a surprisingly good fit to the lattice results for the gluon plasma, and for 2-flavor, 3-flavor and $(2+1)$-flavor QGP. The basic idea is first to evaluate the energy density ε from the grand partition function of quasi-particle QGP, and then derive all other thermodynamic functions from ε. Quasi-particles are assumed to have a temperature dependent mass equal to the plasma frequency. Energy density, pressure and speed of sound at zero chemical potential are evaluated and compared with the available lattice data. We further extend the model to a finite chemical potential, without any new parameters, to obtain the quark density, quark susceptibility etc., and the model fits very well with the lattice results on 2-flavor QGP.

PACS. 12.38.Mh; 12.38.Gc; 05.70.Ce; 52.25.Kn

1 Introduction

The non-ideal behavior of QGP seen in lattice simulations [1–5] of QCD, and the elliptical flow observed in relativistic heavy ion collisions (RHICs) led to a hot debate on the nature of QGP near the critical temperature, T_c [6]. Various models such as

(a) QGP with confinement effects,
(b) strongly interacting QGP (sQGP),
(c) strongly coupled quark–gluon plasma (SCQGP), and
(d) quasi-particle QGP (qQGP).

In model (a), confinement effects like the bag constant [7, 8], the Cornell potential [9] etc. are assumed to give rise to the non-ideal behavior of QGP. In (b) [10], the effects of the bound states of colorless as well as colored hadron resonances are assumed to be responsible. In (c) [11, 12], it is assumed that QGP near T_c is what is called a strongly coupled plasma (SCP) and the equation of state (EoS) of SCP in QED with proper modifications for QCD fits very well with the lattice data. In (d), QGP is made up of quasi-particles with a temperature dependent mass [13, 14]. Different varieties of qQGP were proposed in order to make the theory thermodynamically consistent as well as consistent with perturbative and non-perturbative calculations of QCD [15, 16].

Here we revisit qQGP with a new method, which involves a smaller number of parameters, to derive the EoS of QGP, first at zero chemical potential μ. Here by μ is meant the chemical potential of the quark, which is one third of the baryon chemical potential. We start from the energy density, rather than the pressure as done earlier, and we derive various thermodynamic properties by fixing the parameters of the model. Further we extend the model to include a finite chemical potential and obtain the quark density (n_q), the change in pressure (ΔP) due to the finite μ and the quark susceptibility for 2-flavor QGP.

2 Phenomenological model

The basic assumption in this model is that the thermal properties of QGP may be explained by the properties of the thermal excitations of the interacting quarks and gluons in QGP, which are called quasi-particles. We know from the quasi-particle description of vibrations in solids due to the interactions between atoms, known as the problem of the specific heat in solids, that classical vibrations or waves obeying a certain dispersion relation are quantized to give elementary excitations or quasi-particles like phonons [17]. Then the thermodynamics of such a system of quasi-particles is studied using the classical dispersion relation, and it fits well with the experimental results. Similarly, here we assume that QGP at finite temperature is pictured as a system of free quasi-particles with the quantum numbers of the quarks and gluons with thermal masses. The thermal mass arises because of the collective effects of the plasma, and hence we take it to be equal to the plasma frequency, ω_p. We assume the simple dispersion

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relation $\omega^2 = k^2 + \omega_{\rm p}^2$. In the case of systems with massive quarks, like in $(2+1)$-flavor QGP, the rest mass needs to be included, as will be discussed at the end of the Sect. 3.

Following the standard procedure of statistical mechanics [17], the grand partition function is given by

$$Q_G = \sum_{s,r} \mathrm{e}^{-\beta E_r - \alpha N_s}\,, \tag{1}$$

where the sum is over the energy states E_r and the particle number states N_s. α and β are defined as $\alpha \equiv -\mu/T$ and $\beta \equiv 1/T$. Now we assume that QGP is made up of non-interacting quasi-partons, and, on taking the thermodynamic limit, we get

$$q \equiv \ln Q_G = \mp \sum_{k=0}^{\infty} \ln(1 \mp z\mathrm{e}^{-\beta\epsilon_k})\,, \tag{2}$$

where q is called the q-potential, and $\mp$ is for bosons and fermions. $z \equiv \mathrm{e}^{\mu/T} = \mathrm{e}^{-\alpha}$ is called the fugacity. ϵ_k is the single particle energy, given by

$$\epsilon_k = \sqrt{k^2 + m^2(T,\mu)}\,,$$

where k is the momentum and m is the mass, which is equal to $\omega_{\rm p}$. ϵ_k, obtained from the simple dispersion relation discussed earlier, is an approximation of an exact dispersion relation, as discussed in [18]. A similar approximate relation is also used in the study of thermodynamics of the ultra-relativistic (e, e^+, γ) system [19, 20] with an estimated error of less than 3%. The main effects of the interaction of bare partons, namely collective effects, are taken into a (T, μ) dependent mass term, and we treat them as non-interacting quasi-partons. With this assumption, the average energy U, by definition, is given by

$$U \equiv \langle E_r \rangle = \frac{\sum_{s,r} E_r \mathrm{e}^{-\beta E_r - \alpha N_s}}{Q_G}\,, \tag{3}$$

which may be further simplified as

$$= -\frac{\sum_{s,r}\left(\frac{\partial}{\partial\beta}\mathrm{e}^{-\beta E_r - \alpha N_s}\right)_{\alpha,V,m}}{Q_G} = -\left(\frac{\partial}{\partial\beta}\ln Q_G\right)_{\alpha,V,m}\,, \tag{4}$$

where $E_r \equiv \sum_k \epsilon_k\, n_k + E_0$ for the many particle energy state. E_0 is the vacuum energy, which we neglect as an approximation without any TD inconsistency, as will be discussed later. In quasi-particle models E_r depends on T and μ because of the thermal mass m. Next, on substituting for $\ln Q_G$ from (2) and on performing a partial differentiation, we get

$$U = \sum_k \frac{z\epsilon_k \mathrm{e}^{-\beta\epsilon_k}}{1 \mp z\mathrm{e}^{-\beta\epsilon_k}}\,. \tag{5}$$

Now, on taking the continuum limit and after some algebra, we get

$$\varepsilon = \frac{g_f T^4}{2\pi^2}\sum_{l=1}^{\infty}(\pm 1)^{l-1} z^l \frac{1}{l^4} \times \left[\left(\frac{m\,l}{T}\right)^3 K_1\left(\frac{m\,l}{T}\right) + 3\left(\frac{ml}{T}\right)^2 K_2\left(\frac{ml}{T}\right)\right]\,, \tag{6}$$

where g_f is the degeneracy, equal to $g_g \equiv 16$ for gluons and equal to $12n_f$ for quarks. n_f is the number of flavors. K_1 and K_2 are modified Bessel functions of order 1 and 2 respectively. The above equations, (5) and (6), are the same as in [21] for the energy density, except for the vacuum energy term, $B(T)$.

3 Thermodynamics (ε, P, C_s^2) of QGP with zero μ

Let us first consider the EoS of QGP with zero chemical potential and take $z = 1$. Hence we get the energy density, which, expressed in terms of $e(T) \equiv \varepsilon/\varepsilon_s$, for the quark–gluon plasma of quasi-partons is

$$e(T) = \frac{15}{\pi^4}\frac{1}{\left(g_g + \frac{21}{2}n_f\right)}\sum_{l=1}^{\infty}\frac{1}{l^4}\left(g_g\left[\left(\frac{m_g l}{T}\right)^3 K_1\left(\frac{m_g l}{T}\right) + 3\left(\frac{m_g l}{T}\right)^2 K_2\left(\frac{m_g\, l}{T}\right)\right] + 12n_f(-1)^{l-1} \times\left[\left(\frac{m_q l}{T}\right)^3 K_1\left(\frac{m_q l}{T}\right) + 3\left(\frac{m_q l}{T}\right)^2 K_2\left(\frac{m_q l}{T}\right)\right]\right)\,, \tag{7}$$

where ε_s is the Stefan–Boltzmann gas limit of QGP, which may be obtained by taking the high temperature limits of (6) for gluons and quarks separately and adding them. m_g is the temperature dependent gluon mass, which is equal to the plasma frequency, i.e, $m_g^2 = \omega_{\rm p}^2 = \frac{g^2T^2}{18}(2N_c + n_f)$. This is obtained from finite temperature perturbative calculations [18, 22]. Note that both gluons and quarks contribute to the gluon mass. However, in the case of m_q, the temperature dependent mass of the quarks, we take $m_q^2 = \frac{g^2T^2}{18}n_f$ and no contribution from the gluons ($N_c = 0$). This is our assumption that the quasi-quarks are the thermal excitations of plasma collective modes due to quarks only, with different flavors n_f. g^2 is related to the two-loop order running coupling constant, given by

$$\alpha_{\rm s}(T) \equiv \frac{g^2}{4\pi} = \frac{6\pi}{(33-2n_f)\ln(T/\Lambda_T)} \times\left(1 - \frac{3(153-19n_f)}{(33-2n_f)^2}\frac{\ln(2\ln(T/\Lambda_T))}{\ln(T/\Lambda_T)}\right)\,, \tag{8}$$

where Λ_T is a parameter related to the QCD scale parameter. This choice of $\alpha_{\rm s}(T)$ is motivated by lattice simulations. With these values of the masses, with the above $\alpha_{\rm s}$, we can evaluate the $e(T)$ from (6). Note that the only temperature dependence in $e(T)$ comes from $\alpha_s(T)$, which has the same form as that of lattice simulations [1,2] with Λ_T as a free parameter. The pressure can be calculated from the thermodynamic relation,

$$\varepsilon = T\frac{\partial P}{\partial T} - P\,, \tag{9}$$

and we get

$$\frac{P}{T} = \frac{P_0}{T_0} + \int_{T_0}^{T} \mathrm{d}T \frac{\varepsilon(T)}{T^2}\,, \tag{10}$$

where P_0 and T_0 are the pressure and temperature at some reference points.

Note that the standard relation of pressure and q-potential is not valid here because of the temperature dependent ϵ_k. We can rederive it using the same procedure as used by Pathria [17], as follows (more details are in [23]):

$$\delta q = \frac{1}{Q_G}\left[\sum_{r,s} \mathrm{e}^{-\beta(E_r-\mu N_s)}\left(-E_r\delta\beta - \beta\delta E_r + N_s\delta(\beta\mu)\right)\right] \tag{11}$$

$$\frac{PV}{T} = q + \int \mathrm{d}\beta\beta\frac{\partial m}{\partial \beta}\left\langle \frac{\partial E_r}{\partial m}\right\rangle$$
$$\frac{PV}{T} = \mp\sum_{k=0}^{\infty} \ln\left(1\mp z\mathrm{e}^{-\beta\epsilon_k}\right) + F(T)V\,. \tag{12}$$

Therefore, the standard relation of pressure and q-potential is not thermodynamically consistent here. One needs an extra term because of the temperature dependent mass. In fact this extra term removes the thermodynamic inconsistency of the original qQGP model, which was first noticed by Gorenstein and Yang [21]. They found that, with the standard relation of pressure and q-potential, the thermodynamic relation, (9), is not obeyed with the temperature dependent mass. However, with the extra term we get from (12)

$$\frac{\partial P}{\partial T} = \frac{P}{T} + \frac{\varepsilon}{T} - \frac{1}{V}\left\langle\frac{\partial \epsilon_k}{\partial T}\right\rangle + \frac{1}{V}\left\langle\frac{\partial E_r}{\partial T}\right\rangle\,, \tag{13}$$

where the last two terms exactly cancel (following the trick used in deriving (5)), and hence the thermodynamic relation, (9), is obeyed. Note that Gorenstein and Yang reformulated the statistical mechanics to solve it [14,21], which is not necessary as we have shown here. Of course, we have not included the vacuum energy contribution here. A similar TD consistent analysis with vacuum energy is reported in [23].

However, we follow the standard statistical mechanics and thermodynamics and avoid using (12), and instead we use (10) to evaluate the pressure. Once we know P and ε, $c_s^2 = \frac{\partial P}{\partial \varepsilon}$ can be evaluated.

Let us now reformulate the above discussion for QGP with massive quarks, like the $(2+1)$-flavor system of [5]. It is a QGP with two light quarks (u) and one heavy quark (s) along with gluons. Hence we get the result that the energy density, expressed in terms of $e(T) \equiv \varepsilon/\varepsilon_s$, for the quark–gluon plasma of quasi-partons is

$$\begin{aligned} e(T) &= \frac{15}{\pi^4}\frac{1}{\left(g_g + \frac{21}{2}n_f^{\mathrm{eff}}\right)}\sum_{l=1}^{\infty}\frac{1}{l^4} \\ &\times\left(g_g\left[\left(\frac{m_g l}{T}\right)^3 K_1\left(\frac{m_g l}{T}\right) + 3\left(\frac{m_g l}{T}\right)^2 K_2\left(\frac{m_g l}{T}\right)\right]\right. \\ &+ 24(-1)^{l-1} \\ &\times\left[\left(\frac{m_u l}{T}\right)^3 K_1\left(\frac{m_u l}{T}\right) + 3\left(\frac{m_u l}{T}\right)^2 K_2\left(\frac{m_u l}{T}\right)\right] \\ &+ 12(-1)^{l-1} \\ &\times\left.\left[\left(\frac{m_s l}{T}\right)^3 K_1\left(\frac{m_s l}{T}\right) + 3\left(\frac{m_s l}{T}\right)^2 K_2\left(\frac{m_s l}{T}\right)\right]\right)\,, \end{aligned} \tag{14}$$

where m_g, m_u, m_s are the masses of gluon, up quark and strange quark, respectively, including both the rest mass and the thermal mass. n_f^{eff} is the effective number of flavors and is not equal to 3 because of the finite rest masses of the quarks [5]. The masses of the quarks are modified as

$$m_q^2 = m_{q0}^2 + \sqrt{2}\,m_{q0}\,m_{\mathrm{th}} + m_{\mathrm{th}}^2\,, \tag{15}$$

following the idea used in other qQGP models for a system with finite quark masses. But the difference is that our m_{th} is equal to the plasma frequency due to quarks alone. That is, $m_{\mathrm{th}}^2 = \omega_{\mathrm{p}}^2 = \frac{g^2T^2}{18}n_f$. m_{q0} is the rest mass of the up or strange quark. g^2 in the thermal masses is related to the two-loop order running coupling constant, as before.

In summary, our phenomenological model of qQGP differs from the other ones in its formalism, the model for the thermal masses, the model for $\alpha_s(T)$, the number of adjustable parameters and there being no TD inconsistency or TD consistency relation. It is remarkable that this model, with a single system dependent parameter, explains many lattice results of the Bielefeld group [1–5,24], as shown here, as well the lattice results of Fodor et al. [25], as shown in [26].

4 Thermodynamics (n_q, ΔP, χ_q) of QGP with finite μ

Recently, there have been a lot of attempts to simulate QCD with finite μ on the lattice, and results are reported in [25,27] etc. Here we consider the recent results of Allton et al. [27] for 2-flavor QGP and try to extend our model to finite μ and explain their results. Again using the standard procedure of statistical mechanics, we have

$$\begin{aligned}\langle N\rangle &= \frac{\sum_{s,r} N_s \mathrm{e}^{-\beta E_r - \alpha N_s}}{Q_G} \\ &= -\frac{\sum_{s,r}\left(\frac{\partial}{\partial\alpha}\mathrm{e}^{-\beta E_r-\alpha N_s}\right)_{\beta,V,m}}{Q_G}\,,\end{aligned} \tag{16}$$

which, on further simplification, gives

$$= -\left(\frac{\partial}{\partial \alpha} \ln Q_G\right)_{\beta,V,m} = z\left(\frac{\partial}{\partial z} \ln Q_G\right)_{\beta,V,m}$$
$$= \sum_k \frac{z\mathrm{e}^{-\beta\epsilon_k}}{1 \mp z\mathrm{e}^{-\beta\epsilon_k}} \,. \quad (17)$$

In the continuum limit and after some algebra, the above reduces to

$$\frac{n_q}{T^3} = \frac{12}{\pi^2} \sum_{l=1}^{\infty} (-1)^{l-1} \frac{1}{l^3} \left[\left(\frac{m_q l}{T}\right)^2 K_2\left(\frac{m_q l}{T}\right) \sinh\left(\frac{\mu l}{T}\right) \right]. \quad (18)$$

Now we modify the earlier $m_q^2(T)$ to $m_q^2(T,\mu)$ as follows:

$$m_q^2(T,\mu) = \frac{g^2 T^2}{18} n_f \left(1 + \frac{\mu}{\pi^2 T^2}\right), \quad (19)$$

inspired by QCD perturbative calculations [28]. In our case $n_f = 2$, and g^2 is related to the two-loop order running coupling constant, discussed earlier, but it needs to be modified to take account of the finite μ. Following the work of Schneider [29] and Letessier and Rafelski [30], we now change T/Λ_T in (8) to

$$\frac{T}{\Lambda_T}\sqrt{1 + a\frac{\mu^2}{T^2}}\,, \quad (20)$$

where a is equal to $(1.91/2.91)^2$ in the calculation of Schneider for $\mu/T \leq 1$ and $1/\pi^2$ in the phenomenological model of Letessier and Rafelski.

From n_q, we may obtain other thermodynamic quantities, like

$$\Delta P \equiv P(T,\mu) - P(T,0) = \int_0^{\mu} n_q \, \mathrm{d}\mu \quad (21)$$

and

$$\chi_q = \frac{\partial n_q}{\partial \mu}|_{\mu=0} \,. \quad (22)$$

5 Results

It is interesting to see that this simple model very nicely fits the lattice data [1–5] on all four systems, namely, the gluon plasma, and 2-flavor, 3-flavor and $(2+1)$-flavor QGP in the case of a zero chemical potential. In Fig. 1, we plotted $P(T)/T^4$ versus T for pure gauge, 2-flavor, 3-flavor and $(2+1)$-flavor QGP, along with the lattice results. Note that, in the case of flavored QGP, since there is $(10\% \pm 5\%)$ uncertainty in the P data [5], on taking the continuum limit with massless quarks, we multiply the lattice data by the factor 1.1 and then made the plot. For each system, the Λ_T are adjusted, so that we get a good fit to the lattice results. We have fixed P_0 from the lattice data at the critical temperature T_c for each system. A surprisingly good fit is obtained for all systems with Λ_T/T_c equal to 0.65, 0.7, 0.5 and 0.5 for the gluon plasma, and 2-flavor, 3-flavor and $(2+1)$-flavor QGP, respectively. We have taken n_f equal to 0, 2 and 3, respectively, for our four systems. In the case of $(2+1)$-flavor QGP [5], $n_f^{\mathrm{eff}} = (2 \times 0.9672 + 1 \times 0.8275)$, and the rest masses are $m_{uo}/T = .4$, $m_{so}/T = 1$.

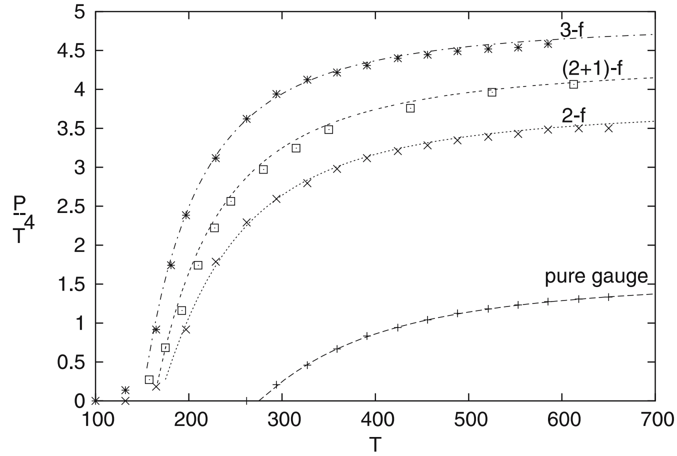

Fig. 1. Plots of P/T^4 as a function of T from our model and lattice results (*symbols*) for pure gauge, 2-flavor, $(2+1)$-flavor and 3-flavor QGP

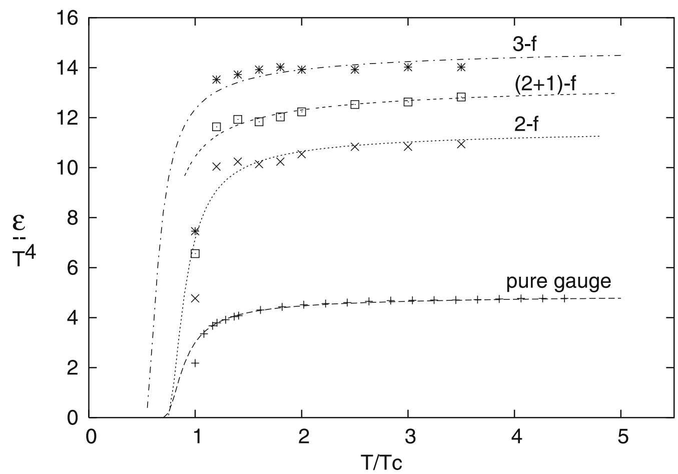

Fig. 2. Plots of ε/T^4 as a function of T/T_c from our model and lattice results (*symbols*) for pure gauge, 2-flavor, $(2+1)$-flavor and 3-flavor QGP

Once $P(T)$ is obtained, the other macroscopic quantities may be derived from $P(T)$, and no other parameters are needed. In Fig. 2, we plotted ε/T^4 versus T/T_c for all four systems along with the lattice results [24], and it fits well, without any extra parameters. All the four curves look similar, but there are shifts to the left as the flavor content increases. We have taken T_c equal to 275, 175, 155 and 175 MeV respectively for the gluon plasma, and 2-flavor, 3-flavor and $(2+1)$-flavor QGP.

In Fig. 3, c_s^2 is plotted for three systems with massless quarks, again with the lattice results for the gluon plasma. A reasonably good fit for the gluon plasma and our model's outcome for the flavored QGP is obtained. All three

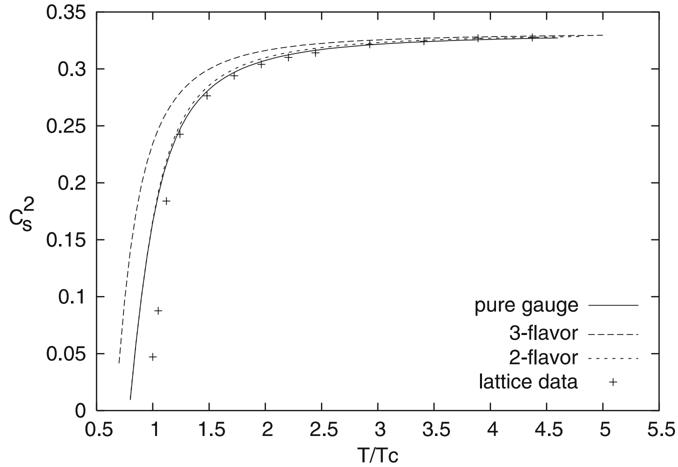

Fig. 3. Plots of c_s^2 as a function of T/T_c from our model for pure gauge (*lower curve*), 2-flavor QGP (*middle curve*) and 3-flavor QGP (*upper curve*) and also with lattice data for pure gauge

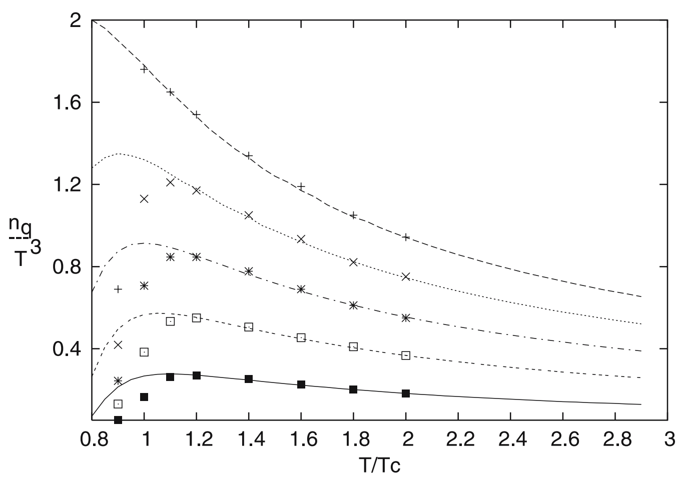

Fig. 4. Plots of n_q/T^3 as a function of T/T_c from our model of 2-flavor QGP and also with lattice data (*symbols*) [27]

curves have a similar behavior, i.e, a sharp rise near T_c and then flattening to a value close to 1/3. c_s^2 is larger for larger flavor content. For 2-flavor QGP, it almost coincides with that of the gluon plasma.

In Fig. 4, n_q/T^3 is plotted for 2-flavor QGP and compared with recent lattice data without any new parameters. The only parameter needed is Λ_T, which has been fixed by the results of QGP with zero μ before. For different values of μ/T_c, all curves have a similar behavior and very nicely fit with the lattice points for $T \geq 1.2\,T_c$. Note that this result is for $a = (1.91/2.91)^2$ [29] in (20). For the other value, $a = 1/\pi^2$ [30], the results are not satisfactory, even though both results coincide for $T > 1.5T_c$.

$\Delta P/T^4$ and χ_q/T^2 are plotted in Figs. 5 and 6 and again fit with the lattice results. Note that, also in the case of finite μ, we multiply the lattice data by a factor 1.1 as we did for the $\mu = 0$ case.

Very close to $T = T_c$, i.e., $T < 1.2T_c$, the results of our model are not good, especially for ε, c_s^2, n_q etc. Probably, by including the "zero-mode" energy (the energy in the absence of quasi-particles), which may contribute a term like the $B(T, \mu)$ of the other qQGP models to the pressure and energy density, in a thermodynamically consistent way, we may improve our results. Further, the lattice data also have large error bars very close to T_c. However, except for a small region at $T = T_c$, our results are very good for all regions of $T > T_c$. For $T < T_c$, our model is not applicable anyway, because the system may not be in a plasma state.

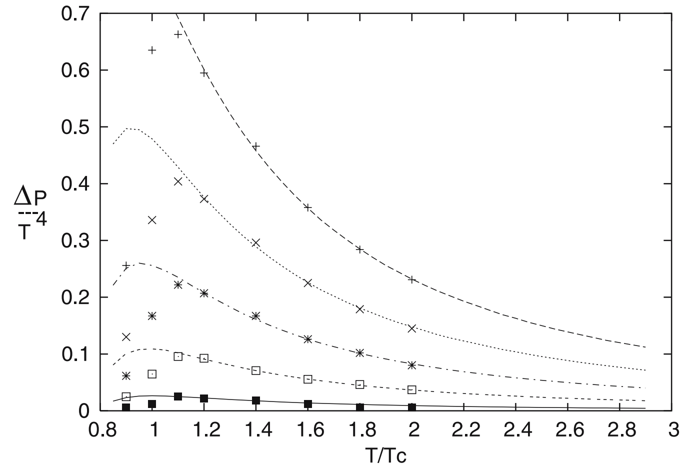

Fig. 5. Plots of $\Delta P/T^4$ as a function of T/T_c from our model of 2-flavor QGP and also with lattice data (*symbols*)

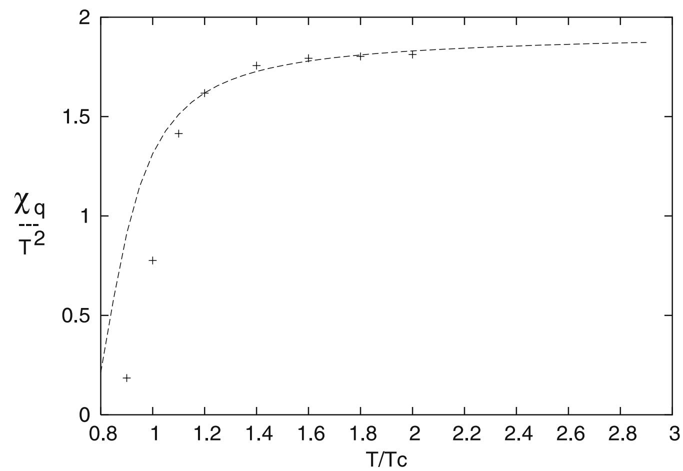

Fig. 6. Plots of χ_q/T^2 as a function of T/T_c from our model of 2-flavor QGP and also with lattice data (*symbols*)

6 Conclusions

We revisited the quasi-particle picture of QGP with a new method with less parameters. By this method we derive the energy density $\varepsilon(T)$ first and *not* $P(T)$ as done earlier, and only then we derive $P(T)$, c_s^2 etc. QGP is assumed to consist of non-interacting quasi-partons with temperature and chemical potential dependent masses. The interactions among bare partons lead to collective effects in QGP, which leads to quasi-particles, having the quantum numbers of gluons and quarks, with their masses equal to the plasma frequencies. The plasma frequency depends on the running coupling constant, and we used the 2-loop order $\alpha_s(T,\mu)$, which is similar to that of lattice simulations, with one parameter related to the QCD scale parameter. The thermodynamic properties of QGP depends on this parameter. To get the pressure, we need one integration constant, which we fix to the lattice point at T_c. It is not a parameter of the model, because one may as well fix it at $T=\infty$, where the pressure must go to the Stefan–Boltzmann limit. In numerical calculations it is difficult to take this limit. The parameters of our model are different for different systems, like the gluon plasma, and 2-flavor and 3-flavor QGP etc. Using one system dependent parameter, a very good fit to the lattice results was obtained for energy density, pressure, speed of sound, quark density, quark susceptibility etc. No other effects, like a temperature dependent bag pressure, confinement effects, effective degrees of freedom etc., were needed to fit the lattice results. In comparison with other models that generally use more than two system dependent parameters, here, just with one system dependent parameter and using $\alpha_s(T,\mu)$, inspired by the lattice simulation of QCD, we can fit the lattice results very nicely. Hence the non-ideal effects seen in lattice simulations of QCD may be related to collective behavior of QGP. Recently, a very good fit to the lattice results on the EoS of QGP has also been obtained [12] by treating QGP as SCQGP, and again the nature of the EoS is determined by a plasma parameter that depends on the collective properties of the plasma.

Acknowledgements. I thank the organizer and DAE of India for the financial help to attend the International conference on ICPAQGP at Kolkata, India, which inspired me to present this result.

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