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Quark mass scaling and properties of light-quark matter

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Abstract We study the properties of two-flavor quark matter in the equivparticle model. A new quark mass scaling at finite temperature is proposed and applied to the thermodynamics of two-flavor quark matter. It is found that the perturbative interaction has strong effect on quark matter properties at finite temperature and high density. The pressure at the minimum free energy per baryon is exactly zero. With increasing temperature, the energy per baryon increases, while the free energy per baryon decreases.

Keywords Quark matter · Equation of state · Quark mass scaling

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1 Introduction

In many fields of nuclear physics, e.g., the Quantum Chromodynamics (QCD) phase diagram and structure of compact stars, one needs the equation of state of quark matter [1]. In principle, we have the fundamental theory of strong interactions, i.e., QCD. Due to the non-perturbative QCD interaction at relatively lower densities on the one hand, and the so-called sign problem on the other hand, QCD cannot be studied from first principles at finite baryon density. Therefore, one usually resorts to various phenomenological models, e.g., Nambu and Jona-Lasinio model [2], perturbation model [3–5], field correlator method [6], quark-cluster model [7, 8], and many other models [9–20].

A useful way to include interactions among quarks is to use medium-dependent quark masses. In one class of models, namely the quasiparticle models, the quark mass depends on chemical potential and/or temperature [21–30]. In another case, the quark mass depends on density and/or temperature [31–35]. These kinds of models were previously called the density dependent (density and temperature dependent) quark mass models, but the thermodynamic treatment is inconsistent.

In the case of chemical-potential-dependent masses, one can have thermodynamic consistency by adding an additional term to the thermodynamic potential density [22]. In the density-dependent case, it is now clear that the original chemical potentials should be replaced with effective ones when the quark masses become density and temperature dependent [36]. The most recent version is fully thermodynamically self-consistent and is called the equivparticle model [37].

Another important issue in the equivparticle model is the quark mass scaling, i.e., how to parameterize the density dependence of the quark masses. Initially, people mainly emphasize quark confinement, and the interaction part in the quark mass is parameterized to be inversely proportional to the baryon number density [31] for light quarks and later extended to strange quarks [32]. According to the in-medium chiral condensate, it was shown that the interaction quark mass should be inversely proportional to the cubic root of the density [16].

It is true that confinement interactions dominate at lower densities. With increasing densities, however, the perturbative interaction sets in and becomes more and more important and thus should be included. Recently, a new quark mass scaling, considering both the confinement and perturbative interactions, was derived and applied to the investigation of SQM and strange stars [37]. But the important temperature effect was not considered there.

The purpose of the present paper is to study the properties of two-flavor quark matter with the equivparticle model with the inclusion of both confinement and first-order perturbative interaction at finite temperature and density. In Sect. 2, we discuss the quark mass scaling, while in Sect. 3, we give the necessary thermodynamic framework and numerical results. Finally, we summarize the paper in Sect. 4.

2 Quark mass scaling

Originally, the light-quark mass m_q ($q = \mathrm{u/d}$) was assumed to be inversely proportional to density, i.e., [31]

$$m_{\mathrm{u/d}} = \frac{B}{3n_{\mathrm{b}}}, \tag{1}$$

where B is the bag constant and n_{b} is the baryon number density of quark matter. It was soon extended to including strange quarks [33, 34]

$$m_{\mathrm{s}} = m_{s0} + \frac{B}{3n_{\mathrm{b}}}. \tag{2}$$

Based on the in-medium chiral condensates and linear confinement, a new scaling was derived [16]

$$m_q = m_{q0} + \frac{D}{n_{\mathrm{b}}^{1/3}}. \tag{3}$$

This cubic scaling has been extensively applied to the investigations of SQM-related physics, e.g., the QCD phase diagram [36], properties of SQM and strangelets [38] at zero and finite temperature [18, 39], the damping time scale due to the coupling of the viscosity and r mode [40], and the quark–diquark equation of state and compact star structure [41]. The energy per baryon of quark matter becomes infinite for small density, describing effectively quark confinement.

Although the confinement interaction is dominant at lower density, perturbative interactions become more and more important with increasing density. Recently, a new quark mass scaling considers both confinement and first-order perturbative interactions derived [37] as

$$m_q = m_{q0} + \frac{D}{n_{\mathrm{b}}^{1/3}} + Cn_{\mathrm{b}}^{1/3}. \tag{4}$$

The cubic-root scaling in Eq. (3) was extended to include finite temperature [18] as

$$m_q = m_{q0} + \frac{D}{n_{\mathrm{b}}^{1/3}}\left[1 - \frac{8T}{\lambda T_c}\exp\left(-\lambda\frac{T_c}{T}\right)\right], \tag{5}$$

where $\lambda \approx 1.6$ and T_c is the critical temperature from where the confinement effect becomes ignorable.

The advantage of the extension to finite temperature in Eq. (5) is that it is in consistent with the string theory at lower temperature. An obvious disadvantage is that when one extends it to high temperature, it approaches to zero at $T = T_c$, which was previously regarded as a critical temperature. When $T > T_c$, the expression becomes negative, and one has to take a zero value for the interaction part. We can now write Eq. (5) in another form as

$$m_q = m_{q0} + \frac{D}{n_{\mathrm{b}}^{1/3}}\left[1 + \frac{8T}{\lambda T_c}\exp\left(-\lambda\frac{T_c}{T}\right)\right]^{-1}. \tag{6}$$

The new expression in Eq. (6) is equal to that in Eq. (5) at lower temperature. At higher temperature, however, they act very differently: The former becomes inversely proportional to temperature, while the latter is zero.

Observing Eq. (4), we notice that, except for an adjustable constant, the confinement and perturbative interaction terms are reciprocal. Therefore, inspired by Eqs. (4) and (6) we assume that at finite temperature and density quark mass behaves:

$$\begin{aligned} m_q = m_{q0+}&\frac{D}{n_{\mathrm{b}}^{1/3}}\left(1 + \frac{8T}{\Lambda}e^{-\Lambda/T}\right)^{-1} \\ &+ Cn_{\mathrm{b}}^{1/3}\left(1 + \frac{8T}{\Lambda}e^{-\Lambda/T}\right), \end{aligned} \tag{7}$$

where Λ is a temperature scale parameter, comparable with Λ_{QCD}. Comparing the low density limit of Eq. (7) with Eq. (6), we should have $\Lambda = \lambda T_c$. We thus take $\Lambda = 280$ MeV in the present calculations.

The confinement parameter D and the perturbative strength C should be chosen to meet the condition that the minimum energy per baryon of light-quark matter is greater than 930 MeV at zero temperature, in order not to contradict with the conventional nuclear physics.

According to our recent study, $D^{1/2}$ should be bigger than 120 MeV [37] but smaller than 270 MeV [18], and C is smaller than 1 [37]. For the present case of the two-flavor quark matter, we take the modest values $D^{1/2} = 160$ MeV and $C = 0.6$. This choice has the property that the confinement term decreases up to a flex temperature point at about 155 MeV.

In Fig. 1, we show the quark mass as a function of the temperature at the density $n_b = 0.5\,\mathrm{fm}^{-3}$ for the parameters $D^{1/2} = 160$ MeV and $C = 0.6$ with a solid curve. The confinement and perturbative contributions are also plotted, respectively, with dotted and dashed curves. We notice that with increasing temperature, the confinement term in the quark mass becomes less important than the perturbative one.

For the gluon mass, we, according to the first-order perturbative result, use

$$(m_g/T)^2 = \eta\alpha\,\theta(T - T_c), \tag{8}$$

where T_c is the critical temperature of a pure SU(3) gluon gas. The step function, θ, is unity with a nonnegative argument and zero otherwise. The parameter, η, is taken to be $\eta = 15$ in the present calculations, while for the running coupling, we use a fast convergent expansion [42]:

$$\alpha = \frac{\beta_0}{\beta_0^2 \ln(u/\Lambda_T) + \beta_1 \ln\ln(u/\Lambda_T)}, \tag{9}$$

where the beta coefficients are taken to be $\beta_0 = 11/2 - N_f/3$ and $\beta_1 = 51/4 - (19/12)N_f$. In order to include nonperturbative effects, the renormalization subtraction point is assumed to vary linearly with the temperature as

$$u/\Lambda_T = c_0 + c_1 x \tag{10}$$

with $c_0 = 1$, $c_1 = 1/2$, and $x \equiv T/T_c$.

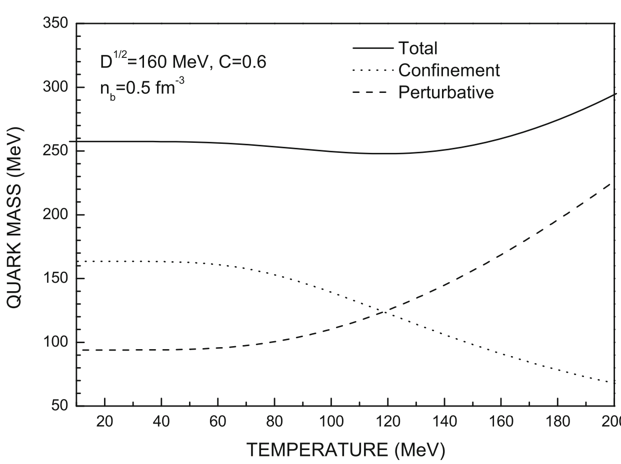

Fig. 1 The temperature dependence of the quark mass at density $n_b = 0.5\,\mathrm{fm}^{-3}$ with the parameters $D^{1/2} = 160$ MeV, $C = 0.6$, and $\Lambda = 280$ MeV

To calculate the properties of quark matter in the equivparticle model, we need to use the density and temperature derivatives of the quark mass, which can be easily obtained from Eq. (7), giving

$$\frac{\partial m_q}{\partial n_b} = -\frac{D}{3n_b^{4/3}}\left(1 + \frac{8T}{\Lambda}e^{-\Lambda/T}\right)^{-1} + \frac{C}{3n_b^{2/3}}\left(1 + \frac{8T}{\Lambda}e^{-\Lambda/T}\right), \tag{11}$$

and

$$\frac{\partial m_q}{\partial T} = -\frac{8D}{\Lambda n_b^{1/3}}\left(1 + \frac{\Lambda}{T}\right)\frac{e^{-\Lambda/T}}{\left(1 + \frac{8T}{\Lambda}e^{-\Lambda/T}\right)^2} + 8Cn_b^{1/3}\left(\frac{1}{T} + \frac{1}{\Lambda}\right)\exp\left(-\frac{\Lambda}{T}\right). \tag{12}$$

The temperature derivative of the gluon mass can be similarly obtained from Eq. (8), i.e.,

$$\frac{\mathrm{d}m_g}{\mathrm{d}T} = \frac{m_g}{T}\left(1 + \frac{x}{2}\frac{\mathrm{d}\ln\alpha}{\mathrm{d}x}\right), \tag{13}$$

where

$$\frac{\mathrm{d}\ln\alpha}{\mathrm{d}x} = -\frac{c_1\alpha}{c_0 + c_1 x}\left[\beta_0 + \frac{\beta_1}{\beta_0}\frac{1}{\ln(c_0 + c_1 x)}\right]. \tag{14}$$

In the literature, there are other forms of the quark mass scaling, e.g., an isospin term was considered in Ref. [43]; Eqs. (1) and (2) were extended to finite temperature by expansion to a Taylor series of temperature [44]; the one-gluon-exchange effect was considered [45]; the asymptotic freedom was explicitly considered by a Wood–Saxon factor [46]. In the present paper, however, we use the quark mass formula in Eq. (7) to study the properties of light-quark matter.

3 Properties of two-flavor quark matter

For simplicity, we assume the system consisting of light quarks and gluons at finite temperature T. According to the equivparticle model, the free particle contribution to the thermodynamic potential density can be written in the form

$$\Omega_0 = \Omega_0^+ + \Omega_0^- + \Omega_0^g, \tag{15}$$

where the equivalent quark (+) and antiquark (−) contributions are

$$\Omega_0^{\pm} = -\frac{d_q T}{2\pi^2}\int_0^\infty \ln\left[1 + e^{-\left(\sqrt{p^2+m_q^2}\mp\mu^*\right)/T}\right]p^2\mathrm{d}p, \tag{16}$$

with the degeneracy factor $d_q = 3(\text{colors}) \times 2(\text{spins}) \times 2(\text{flavors}) = 12$, while the contribution from gluons is

$$\Omega_0^{\rm g} = \frac{d_{\rm g}T}{2\pi^2}\int_0^\infty \ln\left[1-e^{-\sqrt{p^2+m_{\rm g}^2}/T}\right]p^2{\rm d}p. \tag{17}$$

The net quark baryon number density is then

$$n_{\rm b} = \frac{1}{3}\left(n_q^+ - n_q^-\right), \tag{18}$$

where n_q^+ and n_q^- are, respectively, the quark/antiquark number densities:

$$n_q^\pm = \frac{d_q}{2\pi^2}\int_0^\infty \frac{p^2{\rm d}p}{e^{\left(\sqrt{p^2+m_q^2}\mp\mu^*\right)/T}+1}. \tag{19}$$

We emphasize that the quark chemical potential becomes effective due to the density and temperature dependence of the quark mass. The effective chemical potential, μ^*, is related to the actual chemical potential, μ, by

$$\mu = \mu^* + \frac{1}{3}\frac{\partial\Omega_0}{\partial m_q}\frac{\partial m_q}{\partial n_{\rm b}}, \tag{20}$$

where ${\rm d}m_q/{\rm d}n_{\rm b}$ is given in Eq. (11) and the derivative of Ω_0, with respect to m_q, is given by

$$\frac{\partial\Omega_0}{\partial m_q} = \frac{d_q m_q}{2\pi^2}\int_0^\infty\left[\frac{1}{e^{\left(\sqrt{p^2+m_q^2}-\mu^*\right)/T}+1} + \frac{1}{e^{\left(\sqrt{p^2+m_q^2}+\mu^*\right)/T}+1}\right]\frac{p^2{\rm d}p}{\sqrt{p^2+m_q^2}}. \tag{21}$$

The pressure of light-quark matter at finite temperature is

$$P = -\Omega_0 + n_{\rm b}\frac{\partial m_q}{\partial n_{\rm b}}\frac{\partial\Omega_0}{\partial m_q} \tag{22}$$

with the second term on the right-hand side of the above equation arising due to the density dependence of the quark mass. The entropy density reads

$$S = -\frac{\partial\Omega_0}{\partial T} - \sum_{i=q,g}\frac{\partial m_i}{\partial T}\frac{\partial\Omega_0}{\partial m_i},, \tag{23}$$

while the free energy density is given by

$$F = \Omega_0 + 3n_{\rm b}\mu^*. \tag{24}$$

Therefore, the energy density can be obtained by substituting Eqs. (23) and (24) into the thermodynamic relation $E = F + TS$, which leads to

$$E = \Omega_0 + 3n_{\rm b}\mu^* + TS. \tag{25}$$

For a given pair of the density, $n_{\rm b}$, and temperature, T, we can first solve Eq. (18) to obtain the effective chemical potential, μ^*, and the thermodynamic properties can be calculated by Eqs. (22)–(25). Please note, in these expressions, the contribution from gluons has already been included.

In Fig. 2, we show the energy per baryon as functions of the density at the fixed temperature values of $T = 100$ MeV, 150 MeV, and 200 MeV for the parameters $D^{1/2} = 160$ MeV and $C = 0.6$. At lower density, the energy per baryon becomes infinitely large, indicating quark confinement. At large baryon density, the energy per baryon also becomes large because the perturbative interactions become gradually important.

The temperature dependence of the energy (dashed) and free energy (solid) per baryon are given in Fig. 3. We notice that the energy per baryon increases with temperature. However, the free energy per baryon decreases with increasing temperature and eventually becomes negative. This is understandable with a view to the relation $F = E - TS$ and the fact that the entropy term $-TS$ dominates at large temperature.

To check the thermodynamic consistency and demonstrate the effect of the perturbative interaction, we separately plot the density dependence of the energy (dashed curves) and free energy (solid) per baryon as a function of the density at the fixed temperature $T = 30$ MeV for $C = 0$ (open square) and $C = 0.6$ (full square) in Fig. 4 where the points marked with a triangle are the minimum, while the points marked with an open circle are the zero pressure. In Fig. 5, the pressure and the corresponding free energy per baryon at $T = 50$ MeV are simultaneously shown. It is clearly seen that the pressure is negative when the density is lower than the density where the free energy is minimum. It is positive otherwise. It is also checked that the quantity $E + P - TS - 3n_{\rm b}\mu$ is zero at arbitrary density and temperature. In fact, combining Eqs. (20) and (22), one can easily get $P = -\Omega_0 + 3n_{\rm b}(\mu - \mu^*)$, i.e., $\Omega_0 = -P + 3n_{\rm b}(\mu - \mu^*)$. Then substituting it into Eq. (25) and combining similar terms, one immediately has

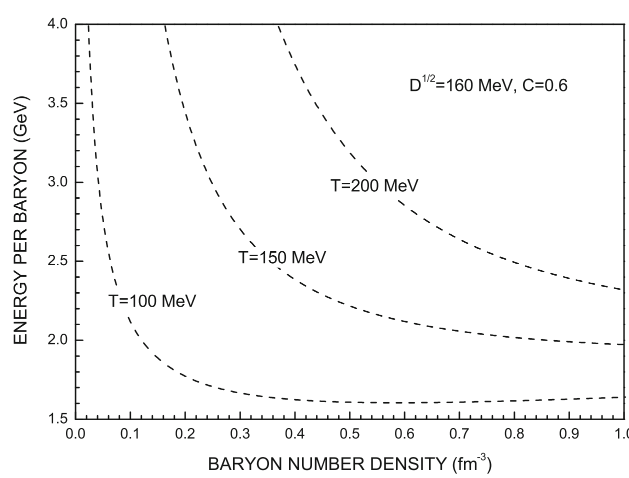

Fig. 2 The density dependence of the energy per baryon at different temperature values

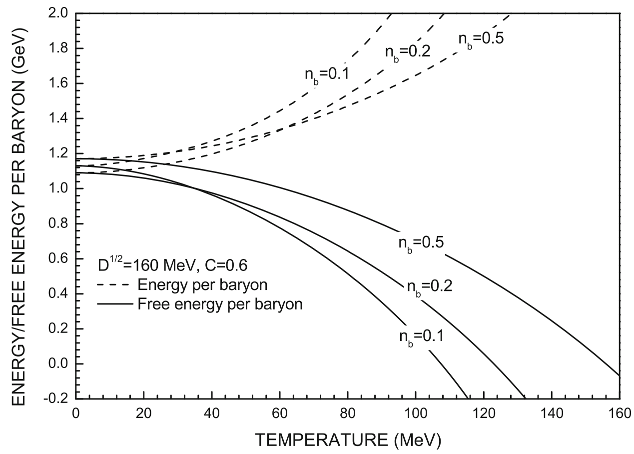

Fig. 3 The temperature dependence of the energy (*dashed*) and free energy (*solid*) per baryon at different densities

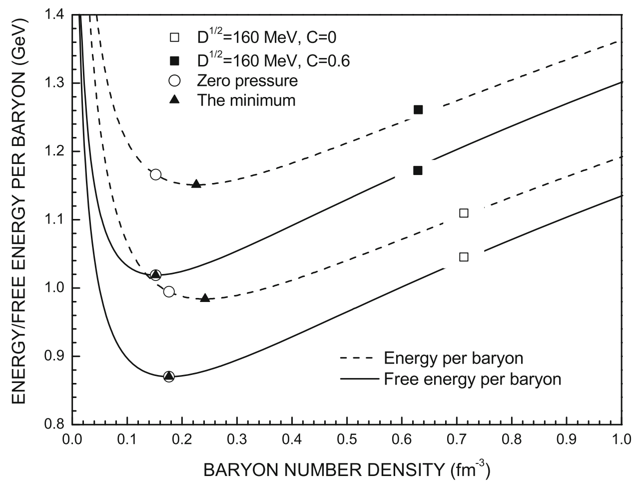

Fig. 4 The energy (*dashed curves*) and free energy per baryon (*solid curves*) of light-quark matter at temperature $T = 30$ MeV. The *triangles* mark the minimum, while the *open circles* label the zero pressured points. We notice that the pressure is exactly zero at the free energy minimum, which is a necessary condition for a consistent thermodynamic treatment

$$E + P - TS - 3n_b\mu = 0. \tag{26}$$

4 Summary

We have studied the properties of light-quark matter in the equivparticle model with a new quark mass scaling at finite density and temperature. Due to the density and temperature dependence of the quark matter, the chemical potential becomes effective, which ensures the thermodynamic consistency: The pressure at the minimum free energy per baryon is exactly zero.

We extend the quark mass scaling with both quark confinement and first-order perturbative interactions to

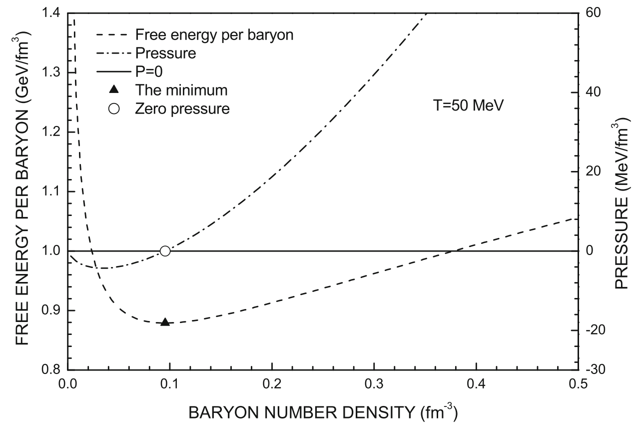

Fig. 5 The pressure and the free energy per baryon of light-quark matter as functions of the baryon number density at $T = 50$ MeV with parameters $D^{1/2} = 160$ MeV and $C = 0.6$

finite temperature and apply it to the investigation of light-quark matter. With increasing temperature, the energy per baryon increases, while the free energy per baryon decreases. The perturbative interaction increases with density and temperature.

It should be pointed out that the present studies are limited to two-flavor quark matter. Extension to the real three-flavor quark matter is a meaningful task and will be done in the near future.

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