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Quark Mass Density- and Temperature- dependent Model for Strange Quark Matter

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Abstract: It is found that the radius for a stable strangelet is a decreasing function of temperature in quark mass density- dependent model. To overcome this difficulty, we extend this model to quark mass density- and temperature- dependent model in which the vacuum energy density at zero baryon density limit B depends on temperature. An ansatz $B=B_0[1-a(T/T_c)+b(T/T_c)^2]$ is introduced and the regions for the best choice of the parameters are studied.

Key words: quark mass-density-dependent model; quark mass density - and temperature- dependent model; strangelet

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It has been expected that a new state of matter, namely, quark-gluon plasma (QGP) would be formed in relativistic heavy-ion collision. Much attention has been attracted to search an unambiguous signature of QGP in recent years. Greiner and his co-workers[1] argued that strangelets might be produced in ultrarelativistic heavy-ion collisions and could serve as an unambiguous signature for the formation of QGP.

Quark mass-density dependent model suggested by Fowler et al[2] has been employed by many authors[2-8] to study strange quark matter (SQM) recently. This model can provide a dynamical description of the confinement mechanism and explain the stability of SQM successfully via the suggestion of a density dependent masses for u, d and s quarks.

We will prove in this paper that a difficulty emerges if the quark mass density-dependent (QMDD) model is used to describe strangelets at finite temperature. The radius of strangelet decreases as the temperature increases. This is of course unreasonable. To overcome this difficulty, considering the fact that the mass of hadrons is observed to be dependent on temperature, we extend the QMDD model to a quark mass density- and temperature- dependent (QMDTD) model, and show, after a suitable choice of the adjusted parameters in the function of $B(T)$, the radius of the strangelet increases with the rise of temperature.

According to QMDD model, the masses of u, d quarks and strange quarks (and the corresponding anti-quarks) are given by [2,4]

$$m_q = \frac{B}{3\tilde{n}_b}, \quad q = u, d, \bar{u}, \bar{d}, \tag{1}$$

$$m_{s,\bar{s}} = m_{s0} + \frac{B}{3\tilde{n}_b}, \tag{2}$$

where $\tilde{n}_b$ is the baryon number density, m_{s0} is the current mass of the strange quark and B is the vacuum energy density inside the bag.

The thermodynamical potential is

$$\Omega = \sum_i \Omega_i$$
$$= -\sum_i T\int_0^\infty \mathrm{d}k\,\frac{\mathrm{d}N}{\mathrm{d}k}\ln[1+\mathrm{e}^{-\beta(\varepsilon_i(k)-\mu_i)}]. \tag{3}$$

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where i stands for u, d, s (or $\bar{u}$, $\bar{d}$, $\bar{s}$) and the electron e (e^+), μ_i is the corresponding chemical potential. The number density $\tilde{n}_i$, the total pressure p and the total energy density ϵ are given by [6]

$$\tilde{n}_i = -\frac{1}{V}\frac{\partial \Omega}{\partial \mu_i}\Big|_{T,\tilde{n}_b} , \tag{4}$$

$$p = -\frac{1}{V}\frac{\partial(\Omega/\tilde{n}_b)}{\partial(1/\tilde{n}_b)}\Big|_{T,\mu_i}$$

$$= -\frac{\Omega}{V} + \frac{\tilde{n}_b}{V}\frac{\partial \Omega}{\partial \tilde{n}_b}\Big|_{T,\mu_i} , \tag{5}$$

$$\epsilon = \frac{\Omega}{V} + \sum_i \mu_i \tilde{n}_i - \frac{T}{V}\frac{\partial \Omega}{\partial T}\Big|_{\mu_i,\tilde{n}_b} \tag{6}$$

respectively. The baryon number density $\tilde{n}_b$ reads

$$\tilde{n}_b = \frac{1}{3}(\tilde{n}_u + \tilde{n}_d + \tilde{n}_s) . \tag{7}$$

The conditions of charge neutrality and chemical equilibrium are

$$2\tilde{n}_u = \tilde{n}_d + \tilde{n}_s + 3\tilde{n}_e , \tag{8}$$

$$\mu_s = \mu_d, \quad \mu_s = \mu_u + \mu_e . \tag{9}$$

Now we are in a position to extend our study to strangelet. Instead of plant wave, the density of states for a sphere with radius R reads[9]:

$$\frac{dN_i}{dk} = g_i\left[\frac{k^2V}{2\pi^2} + f_s^{(i)}\left(\frac{m_i}{k}\right) kS + f_c^{(i)}\left(\frac{m_i}{k}\right) C + \cdots\right] , \tag{10}$$

where $V = 4/3\pi R^3$, $S = 4\pi R^2$, $C = 8\pi R$. $g_i = 6$ for quarks and antiquarks, $g_i = 2$ for e and e^+. The second term on the right hand side of Eq. (10) corresponds to the surface contribution. It is known [10]

$$f_s^{(i)}\left(\frac{m_i}{k}\right) = -\frac{1}{8\pi}\left(1 - \frac{2}{\pi}\arctan\frac{k}{m_i}\right) . \tag{11}$$

The third term was proposed by Madsen[11]

$$f_c^{(i)}\left(\frac{m_i}{k}\right) = \frac{1}{12\pi^2}\left[1 - \frac{3k}{2m_i}\left(\frac{\pi}{2} - \arctan\frac{k}{m_i}\right)\right] . \tag{12}$$

For the strangelets, the stablity condition reads

$$\frac{\partial F}{\partial R} = 0 , \tag{13}$$

where F is the total free energy.

The curves for F per baryon number A vs R of QMDD model at zero temperature and at $T = 50$ MeV are shown in Fig. 1 by solid line and dashed line respectively. The values of A, B, m_{s0} are chosen to be

$$A = 20,\ B = 170\ \text{MeV}\cdot\text{fm}^{-3},$$

$$m_{s0} = 150\ \text{MeV} . \tag{14}$$

It can be seen that the radius determined by the minimum F/A decreases when temperature increases. The resulting temperature dependence of radius R is displayed in Fig. 2. We see that $R(T)$ is a monotonously decreasing function.

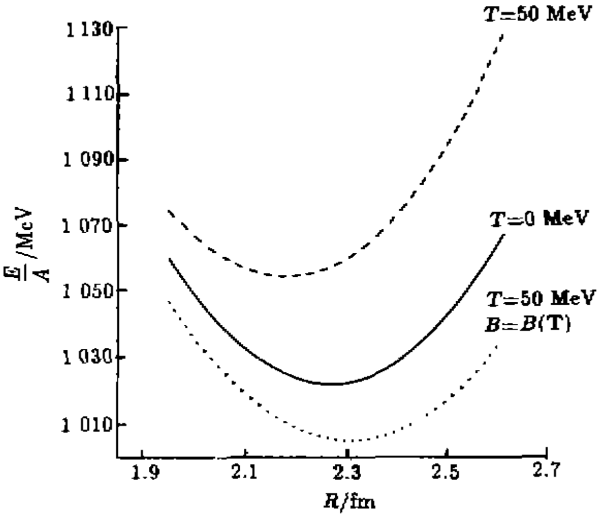

Fig. 1 The free energy per baryon F/A as a function of radius R, for temperature $T = 0$ (—), $T = 50$ MeV in QMDD model (---) and $T = 50$ MeV, parameter $a = 0.65$ in QMDTD model (···).

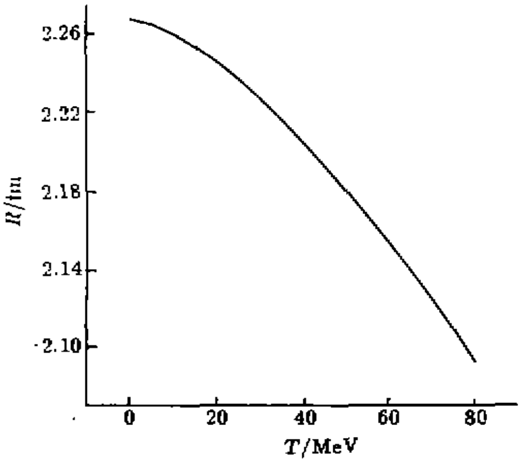

Fig. 2 The radius R as a function of temperature T for QMDD model.

To overcome this difficulty, we introduce an ansatz, namely

$$B = B_0\left[1 - a\left(\frac{T}{T_c}\right) + b\left(\frac{T}{T_c}\right)^2\right], \qquad (15)$$

$$m_q = \frac{B_0\left[1 - a\left(\frac{T}{T_c}\right) + b\left(\frac{T}{T_c}\right)^2\right]}{3\tilde{n}_b}$$

$$(q = u, d, \bar{u}, \bar{d}), \qquad (16)$$

$$m_{s,\bar{s}} = m_{s0} + \frac{B_0\left[1 - a\left(\frac{T}{T_c}\right) + b\left(\frac{T}{T_c}\right)^2\right]}{3\tilde{n}_b}, \qquad (17)$$

where a, b are two adjust parameters, and $T_c = 170$ MeV is the critical temperature of the quark deconfinement phase transition. Since B is zero when $T = T_c$, a condition

$$1 - a + b = 0 \qquad (18)$$

is imposed and only one parameter a can be adjusted.

Introducing Eqs. (16) and (17), we extend the QMDD model to a quark mass density- and temperature-model (QMDTD). The results of our model are shown in Figs. (1), (3) and (4). The F/A vs stable R curve for $T = 50$ MeV, $a = 0.65$ given by QMDTD model is shown in Fig. (1) by dot line. We see that the value of stable radius increases from $R_{(T=0)} = 2.27$ fm to $R_{(T=50\,\mathrm{MeV})} = 2.31$ fm, but, as shown by dashed-line, decreases to $R_{(T=50\,\mathrm{MeV})} = 2.18$ fm for QMDD model.

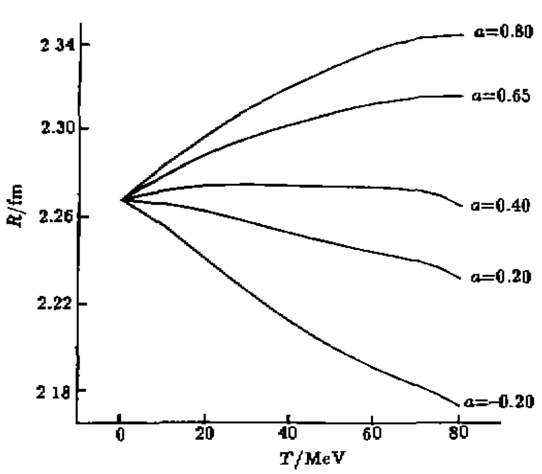

Fig. 3 The radius R as a function of temperature T for QMDTD model with various values for the parameter a as indicated.

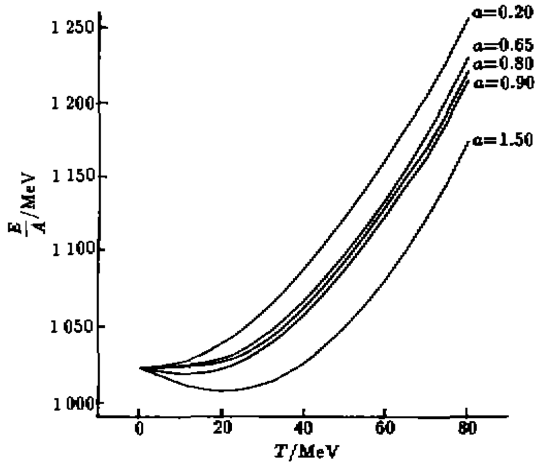

Fig. 4 The energy per baryon E/A as a function of temperature T for QMDTD model with various values for the parameter a as indicated.

The value of parameter a can affect the result significantly. The range of possible a is determined by physical constraints. For example, there are at least two physical constraints: (1) the stable radius R should increase with temperature; (2) the energy per baryon E/A increases with temperature also. To show the importance of first constraint, we plot the $R(T)$ curves for $a = -0.20$, 0.20, 0.40, 0.65, 0.80 in Fig. (3) respectively. It can be seen that $R(T)$ becomes a monotonously increasing function in the regions $0 \leq T \leq 80$ MeV when $a \geq 0.65$. On the other hand, the E/A vs T curves for $a = 1.50$, 0.90, 0.80, 0.65, 0.20 are shown in Fig. (4). We find E/A vs T curves becomes monotonously increasing function in the same temperature region when $a \leq 0.8$. Therefore the best values for parameter a are within

$$0.65 \leq a \leq 0.8. \qquad (19)$$

In summary, in order to overcome the difficulty related to the reduction of R with T, the QMDD model is extended to QMDTD model. An ansatz for the temperature dependence of vacuum energy B (Eq. (15)) is introduced. We find that the parameters a can be chosen in the regions $0.65 \leq a \leq 0.8$. Our model can be used to study strangelet and SQM in bulk.

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奇异夸克物质的夸克质量密度温度相关模型

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摘　要：在夸克质量密度相关模型处理奇异夸克物质滴时，会发现其半径随温度增加而变小. 为克服这一困难，我们通过使口袋常数 B 温度参数化，引入了夸克质量密度温度相关模型. 在这一模型中，$B=B_0[1-a(T/T_c)+b(T/T_c)^2]$，文章中讨论了参数 a、b 的取法.

关键词：夸克质量密度相关模型；夸克质量密度温度相关模型；奇异夸克物质滴