Stability of strangelets at finite temperature

Yun Zhang[1,2] and Ru-Keng Su[3]
[1]*Department of Physics, Fudan University, Shanghai 200433, People's Republic of China*
[2]*Surface Physics Laboratory (National Key Laboratory), Fudan University, Shanghai 200433, People's Republic of China*
[3]*China Center of Advanced Science and Technology (World Laboratory), P.O. Box 8730, Beijing 100080, People's Republic of China*
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Using the quark mass density- and temperature-dependent model, we have studied the thermodynamical properties and the stability of strangelets at finite temperature. The temperature, charge, and strangeness dependences on the stability of strangelets are investigated. We find that the stable strangelets only occur in the high strangeness and high negative charge region.

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I. INTRODUCTION

The study of small lumps of strange quark matter, called strangelets, plays an important role for research the quark gluon plasma (QGP) in recent relativistic heavy ion collision (RHIC) experiments. The reason is that although many signatures of QGP such as J/Ψ suppression, strangeness enhancement, thermal dilepton electromagnetic radiation, etc., have been found [1,2], it is still ambiguous because these signatures can also be explained by hadron gas [3]. To search for an unambiguous signature of QGP is the key for RHIC experiments. The strangelet, as was argued by Greiner *et al.* [4], is a good candidate that could serve as an unambiguous signature for the QGP.

The essential problem for detectability of strangelet in RHIC experiments is to study its stability during the formation of QGP. Employing the MIT bag model, many authors discussed this problem [5–8]. They came to the same conclusion that the electric charge and the strangeness fraction are of vital importance to the experimental searches for strangelets because these two elements affect a change of stability remarkably. But the effect of charge on stability is interpreted differently by different authors. Jaffe and co-workers [5–7] argued that the strangelet has a slight positive charge. They considered strong and weak decay by nucleon and hyperon emission together and concluded that the stable strangelets will have a low but positive change to mass ratio. Contrary to Jaffe and co-workers, after considering the initial condition of possible strangelet production in RHIC carefully, Greiner and co-workers [8] argued that strangelets are most likely highly negatively charged. Here we hope to emphasize that the discussions above are limited in the framework of the MIT bag model and at zero temperature.

Since the quark deconfinement phase transition can occur at high temperature or/and high density only, it is of interest to extend the investigation for the stability of strangelets to finite temperature. This is the objective of this paper.

However, the MIT bag model is a permanent quark confinement model because the confined boundary condition does not change with temperature. In principle, one cannot use this model to study the phase transition of QCD directly. The best that we can do is to employ a model that can almost reproduce the properties of strange quark matter obtained by the MIT bag model, but in which the quark confinement is not permanent. The quark mass density- and temperature-dependent model (QMDTD) [9,10] suggested by us is one of such candidates.

Many years ago, a quark mass density-dependent model (QMDD) was suggested by Fowler, Raha, and Weiner [11] and then it was employed by many authors to discuss the properties of strange quark matter [12–15]. According to the QMDD model, the masses of u,d quarks and strange quarks (and the corresponding antiquarks) are given by

$$m_q=\frac{B}{3n_B} \quad (q=u,d,\overline{u},\overline{d}), \tag{1}$$

$$m_{s,\overline{s}}=m_{s0}+\frac{B}{3n_B}, \tag{2}$$

where n_B is the baryon number density, m_{s0} is the current mass of the strange quark and B is the vacuum energy density. As was proved by Ref. [13], the properties of strange matter in the QMDD model are nearly the same as those obtained in the MIT bag model. In fact, it is not surprising if one notices that the confinement mechanism of the MIT bag model is almost the same as that of QMDD model [9].

But when we employ the QMDD model to discuss the properties of strangelets, many difficulties emerge [9,10]. At first, the radius of the strangelet decreases as the temperature increases; second, it cannot mimic the correct phase diagram of QCD because the temperature T tends to infinity when $n_B\to 0$. To overcome these difficulties, we suggest a QMDTD model [9,10]. Instead of a constant B in QMDD model, we argue that B is a function of temperature and introduced an ansatz [10]

$$B(T)=B_0\left[1-a\left(\frac{T}{T_c}\right)+b\left(\frac{T}{T_c}\right)^2\right], \quad 0\leqslant T\leqslant T_c, \tag{3}$$

$$B(T)=0, \quad T>T_c \tag{4}$$

where B_0 is the vacuum energy density inside the bag (bag constant) at zero temperature, $T_c=170$ MeV is the critical temperature of the quark deconfinement phase transition, and a,b are two adjustable parameters. Since B is zero when $T=T_c$, a condition

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$$1-a+b=0 \tag{5}$$

is imposed and only one parameter a can be adjusted. As pointed out by Ref. [10], in order to satisfy two physical conditions of strangelets at finite temperature, namely, (1) the radius of the strangelet must increase when the temperature increases, and (2) the energy of the strangelet must increase when the temperature increases, the parameter a is restricted in a small range:

$$0.65 \leqslant a \leqslant 0.8. \tag{6}$$

In this paper, we fix the value of the two parameters a,b in this suitable range:

$$a=0.65, \quad b=-0.35. \tag{7}$$

With these parameters set, we use the QMDTD model to discuss the thermodynamical properties of strangelets, in particular, to investigate the stability of strangelets via strong hadron emission and weak hadronic decay. We will study the effects of temperature, charge, and strangeness fraction on the stability and hope that our study can be used for the detectability of the strangelet.

The organization of this paper is as follows. In the following section, we give the formulas of thermodynamical calculations for the QMDTD model. The results of thermodynamical properties of strangelets are presented in Sec. III. In Sec. IV, we will discuss the stability of strangelets via possible strong and weak decays. The last section contains a summary.

II. THERMODYNAMICAL FORMULAS

To calculate the dynamical and thermodynamical quantities of the strangelet, we must look for the density of states first. The density of states of a spherical cavity in which the free particles be contained can be expressed as

$$\rho(k)=\frac{dN(k)}{dk}, \tag{8}$$

where $N(k)$ is the total number of particle states and can be written in terms of dimensionless variable kR as

$$N(k)=A(kR)^3+B(kR)^2+C(kR), \tag{9}$$

where R is the radius of the bag. The three terms of the right-hand side of Eq. (9) refer to the contributions of the volume, surface, and curvature, respectively. The coefficients A, B, and C are expected to be very slow varying functions of kR, and their expressions are model dependent. For the MIT bag model, these coefficients have been obtained by numerical calculations in our previous paper [16]. The volume term A is a constant, and it has the value of

$$A=\frac{2g}{9\pi}, \tag{10}$$

where g is the total degeneracy. For example, it is the total number of spin and color degrees of freedom for a quark with flavor treated separately. The surface term B is

$$B\left(\frac{m}{k}\right)=\frac{g}{2\pi}\left\{\left[1+\left(\frac{m}{k}\right)^2\right]\tan^{-1}\left(\frac{k}{m}\right)-\left(\frac{m}{k}\right)-\frac{\pi}{2}\right\}, \tag{11}$$

where m is the mass of quark. Equations (10) and (11) are in good agreement with those given by multireflection theory [17,18]. The curvature term C cannot be evaluated by this theory except for the two limiting cases $m\rightarrow 0$ and $m\rightarrow\infty$. Madsen proposed that [19]

$$\tilde{C}\left(\frac{m}{k}\right)=\frac{g}{2\pi}\left\{\frac{1}{3}+\left(\frac{k}{m}+\frac{m}{k}\right)\tan^{-1}\frac{k}{m}-\frac{\pi k}{2m}\right\}. \tag{12}$$

But as was pointed out by Ref. [16], the beat fit of numerical data for curvature term is

$$C\left(\frac{m}{k}\right)=\tilde{C}\left(\frac{m}{k}\right)+\left(\frac{m}{k}\right)^{1.45}\frac{g}{3.42(m/k-6.5)^2+100}. \tag{13}$$

Now we are in the position to calculate the thermodynamical quantities of strangelets for the QMDTD model. The thermodynamical potential Ω is

$$\Omega=\sum_i \Omega_i=-\sum_i \frac{g_i T}{(2\pi)^3}\int_0^\infty dk\frac{dN_i}{dk}\ln(1+e^{-\beta[\varepsilon_i(k)-\mu_i]}), \tag{14}$$

where i stands for u,d,s (or $\overline{u},\overline{d},\overline{s}$) quarks, and $g_i=6$ for quarks and antiquarks. dN_i/dk is the density of states for various flavor quarks and is given by Eqs. (8)–(13). μ_i is the corresponding chemical potential (for antiparticles $\mu_{\bar{i}}=-\mu_i$).

$$\varepsilon_i(k)=\sqrt{m_i^2+k^2} \tag{15}$$

is the single-particle energy and m_i is mass for quarks and antiquarks.

According to the QMDTD model [9,10], the masses of quarks are

$$m_{u,\bar{u},d,\bar{d}}=\frac{B_0}{3n_B}\left[1-a\left(\frac{T}{T_c}\right)+b\left(\frac{T}{T_c}\right)^2\right], \quad 0\leqslant T\leqslant T_c, \qquad m_{u,\bar{u},d,\bar{d}}=0, \quad T\geqslant T_c, \tag{16}$$

$$m_{s,\bar{s}}=m_{s0}+\frac{B_0}{3n_B}\left[1-a\left(\frac{T}{T_c}\right)+b\left(\frac{T}{T_c}\right)^2\right], \quad 0\leqslant T\leqslant T_c, \qquad m_{s,\bar{s}}=0, \quad T\geqslant T_c, \tag{17}$$

where m_{s0} is the current mass of the strange quark matter, n_B is the baryon number density

$$n_B=A/V, \tag{18}$$

and A is the baryon number of the strangelet, $V=\frac{4}{3}\pi R^3$ is the volume of the strangelet. Using the standard statistical treatment, and noticing that Ω is not only a function of temperature, volume, and chemical potential, but also of density, it can be proved that the total pressure p and the total energy density ε are given by [13,14,9,10]

$$p=-\frac{1}{V}\frac{\partial(\Omega/n_B)}{\partial(1/n_B)}\bigg|_{T,\mu_i}=-\frac{\Omega}{V}+\frac{n_B}{V}\frac{\partial\Omega}{\partial n_B}\bigg|_{T,\mu_i}, \tag{19}$$

$$\varepsilon=\frac{\Omega}{V}+\sum_i \mu_i n_i-\frac{T}{V}\frac{\partial\Omega}{\partial T}\bigg|_{\mu_i,n_B}. \tag{20}$$

The number density of each particle can be obtained by means of

$$n_i=-\frac{1}{V}\frac{\partial\Omega}{\partial\mu_i}\bigg|_{T,n_B}. \tag{21}$$

At finite temperature, we must include the contributions of the antiparticles; therefore, the baryon number for i quark is given by

$$\Delta N_i=(n_i-n_{\bar{i}})V=\frac{g_i}{(2\pi)^3}\int_0^\infty dk\frac{dN_i}{dk}\left(\frac{1}{\exp[\beta(\varepsilon_i-\mu_i)]+1}-\frac{1}{\exp[\beta(\varepsilon_i+\mu_i)]+1}\right). \tag{22}$$

The strangeness number S of the strangelet reads

$$S=\Delta N_s, \tag{23}$$

and the baryon number A of the strangelet satisfies

$$A=\frac{1}{3}(\Delta N_u+\Delta N_d+\Delta N_s). \tag{24}$$

The electric charge Z of the strangelet is

$$Z=\frac{2}{3}\Delta N_u-\frac{1}{3}\Delta N_d-\frac{1}{3}\Delta N_s. \tag{25}$$

At finite temperature, the stability condition of strangelets for the radius reads

$$\frac{\delta F}{\delta R}=0. \tag{26}$$

where the free energy F of strangelet is

$$F=E-T\tilde{S}, \tag{27}$$

$E=\varepsilon V$ is the total energy, and

$$\tilde{S}=\sum_i \tilde{S}_i=-\sum_i \frac{\partial\Omega}{\partial T}\bigg|_{\mu_i,n_B} \tag{28}$$

is the entropy.

Given the strangeness number, baryon number, and electric charge, for any strangelet, we can calculate chemical potentials for u,d,s quarks self-consistently by Eqs. (23), (24), (25), and (26). Then the thermodynamic potential, free energy, and the stable radius of the strangelet at finite temperature can be obtained self-consistently.

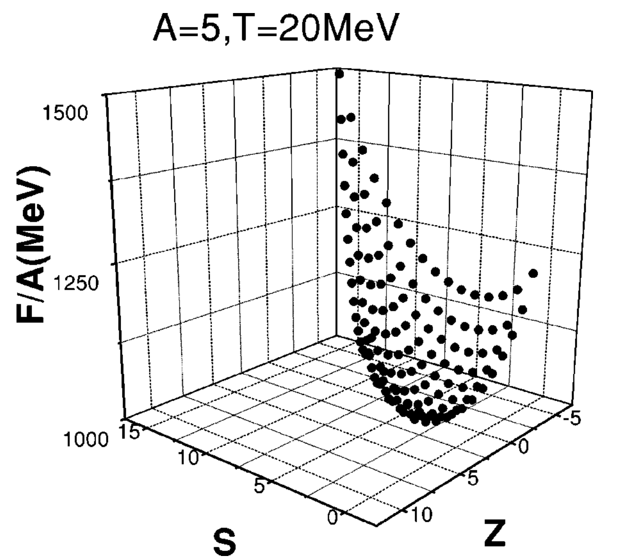

FIG. 1. The dots stand for the free energy per baryon F/A in a S-Z plane for all possible strangelets with $A=5$ and $T=20$ MeV.

III. THERMODYNAMICAL PROPERTIES OF STRANGELETS

The numerical calculations have been done with the parameter set

$$B_0=170\ \text{MeV fm}^{-3},\quad m_{s0}=150\ \text{MeV},$$
$$T_c=170\ \text{MeV}, \tag{29}$$

and the possible area for strangelet in our calculations is chosen as

$$S>0, \tag{30}$$

$$Z\geqslant -A, \tag{31}$$

$$S+Z\leqslant 2A. \tag{32}$$

We calculate the free energy of the strangelet first. Figure 1 shows the free energy per baryon F/A in a S-Z plane for all possible strangelets with $A=5$ and $T=20$ MeV. This is a set of downward protruding curves. The corresponding curves but for $T=50$ MeV are shown in Fig. 2. Comparing these two figures, we find that the positions of dots appearing in Fig. 2 are lower than the corresponding positions (with the same strangeness number S and charge Z) in Fig. 1. For example, for $S=3$ and $Z=-2$, the free energy per baryon of the dot is $F/A=1064.9$ MeV in Fig. 1, but reads $F/A=898.9$ MeV in Fig. 2. For fixed S and Z, the free energy of the strangelet decreases when temperature increases. This result is reasonable because the entropy increases with temperature, the term $T\tilde{S}$ in Eq. (27) increases considerably and

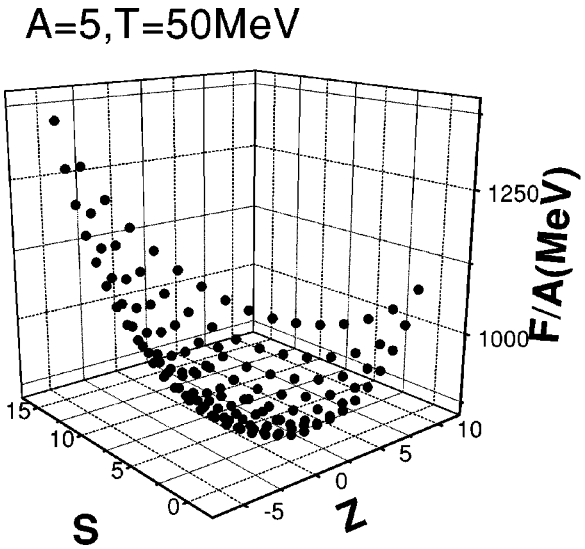

FIG. 2. The same as Fig. 1, but for the temperature $T = 50$ MeV.

F decreases. We will see in the next section this result affects the decay of the strangelet remarkably.

To illustrate our result transparently, we draw the F/A vs S curves for fixed $A=5, Z=-5$ but different temperatures $T=20$ and 50 MeV in Fig. 3, respectively. We find that the minimum of these two curves are located at the same strangeness $S=4$ but with different free energies. The whole curve for $T=20$ MeV is located on the upper position of the curve for $T=50$ MeV. We also draw the F/A vs S curve for $A=10$, $Z=-10$, and $T=50$ MeV in Fig. 4. Compared with Fig. 3, the shape of the curve in Fig. 4 almost does not change except the position of the minimum is changed to $S=8$. These results are similar to that given by Ref. [20].

Now we turn to study the charge and strangeness dependences of the radius of strangelet. We draw F/A vs R curves with fixed $A=5$, $Z=1$, and $T=50$ MeV but different $S=2$, 6, and 9 in Fig. 5, respectively. The stable radii given by Eq. (26) for different strangeness values are different. Figure 5 shows that the stable radius changes from 1.64 to 1.615 fm when the strangeness number changes from 2 to 9. The same curves for $A=5$, $Z=-4$, and $T=50$ MeV but different $S=2,14$ are shown in Fig. 6. We see that the stable radius becomes 1.67 fm for $S=2$ and 1.62 fm for $S=14$. Therefore, we come to the conclusion that the stable radius of strangelet decreases when S increases.

To illustrate the charge dependence of the stable radius, we draw F/A vs R curves with fixed $A=5$, $S=2$, and $T=50$ MeV but different electric charge $Z=1$, 5, and 8 in Fig. 7, respectively. The stable radius increases from 1.64 to 1.69 fm when the electric charge increases from 1 to 8. The same curves for $A=5$, $S=9$, and $T=50$ MeV but different charge $Z=1,-4$ are shown in Fig. 8. We see that the stable radius changes from 1.615 fm to 1.605 fm when Z decreases from 1 to -4. We find that the stable radius of the strangelet increases with electric charge.

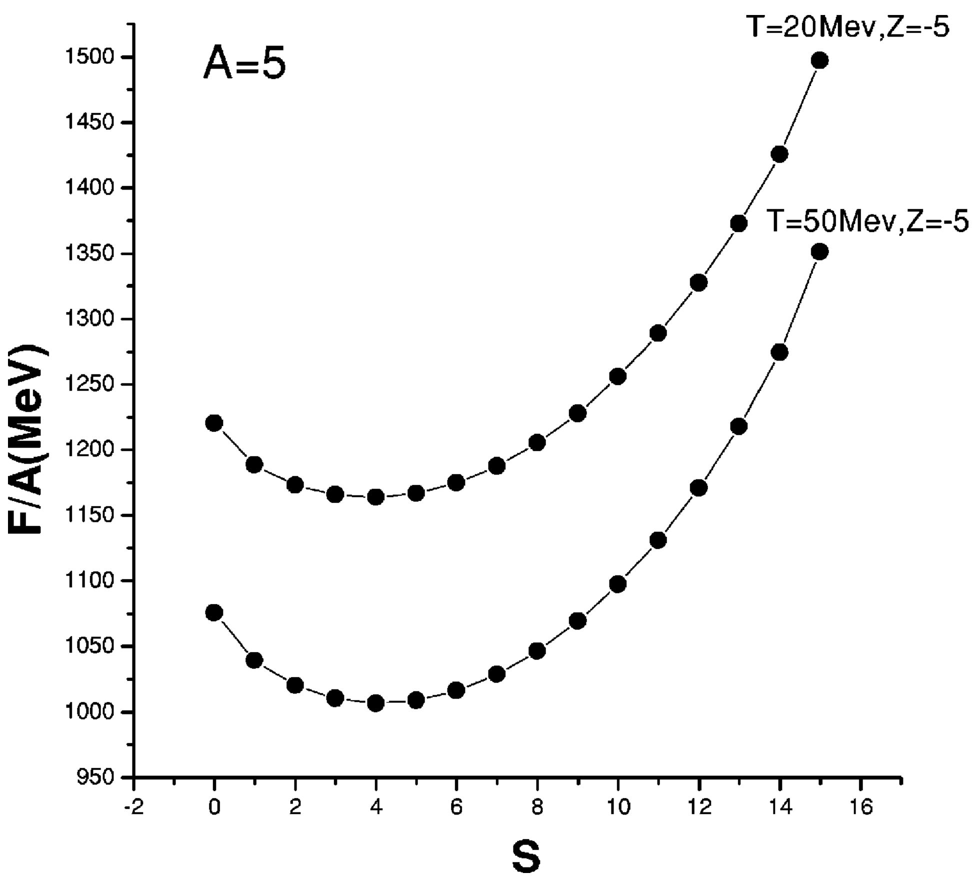

FIG. 3. The free energy per baryon F/A as functions of strangeness number S with $A=5$ and $Z=-5$; the two lines represent the temperature $T=20$ and 50 MeV, respectively.

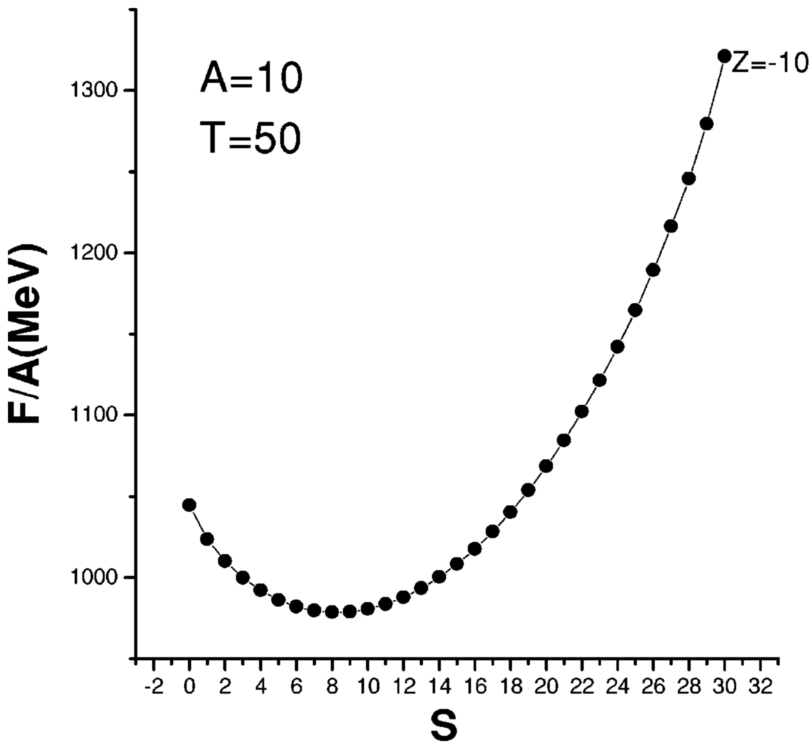

FIG. 4. The free energy per baryon F/A as a function of strangeness number S with $A=10$, $Z=-10$, and $T=50$ MeV.

IV. STABILITY OF THE STRANGELET

In this section, we follow the line of Ref. [8] to investigate the stability of the strangelet and extend their study to finite temperature by using the QMDTD model.

A. Strong decay and unstable strangelets

As was pointed out in Refs. [21,22], small clusters of strange matter are most favored for detection. As two examples, hereafter we study two cases with $A=5$ and $A=10$, respectively.

Instead of the binding energy at zero temperature, we calculate the free energy per baryon of the possible strangelet at finite temperature first. Figures 9 and 10 show the free energy per baryon of all possible strangelets as a function of the strangeness S at the temperature $T=50$ MeV but for $A=5$ and $A=10$, respectively. The solid lines in these two

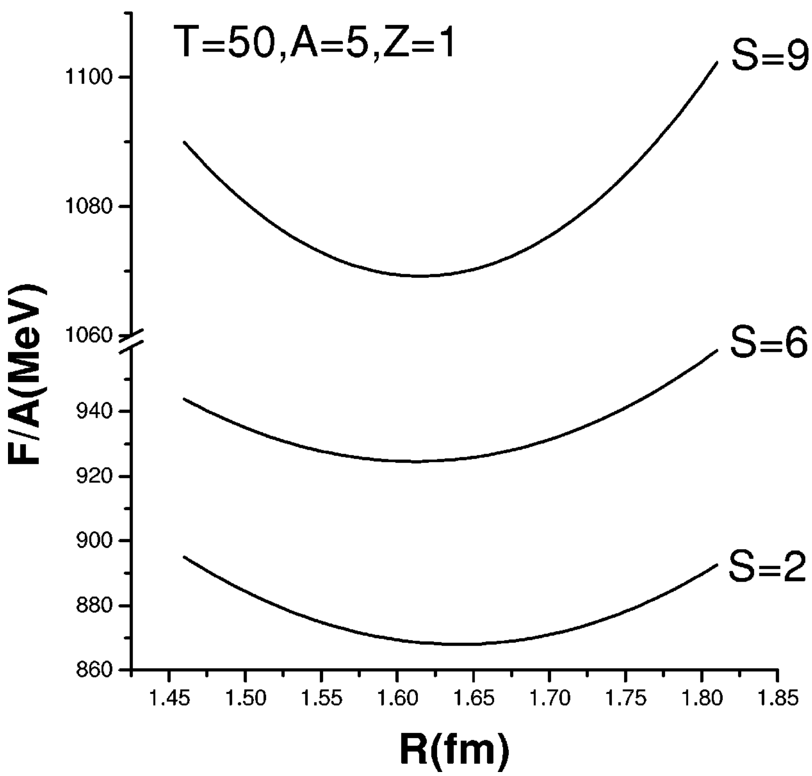

FIG. 5. The free energy per baryon F/A as functions of radius R with $A=5$, $Z=1$, and $T=50$ MeV; the three lines represent the strangeness number $S=2$, 6, and 9, respectively.

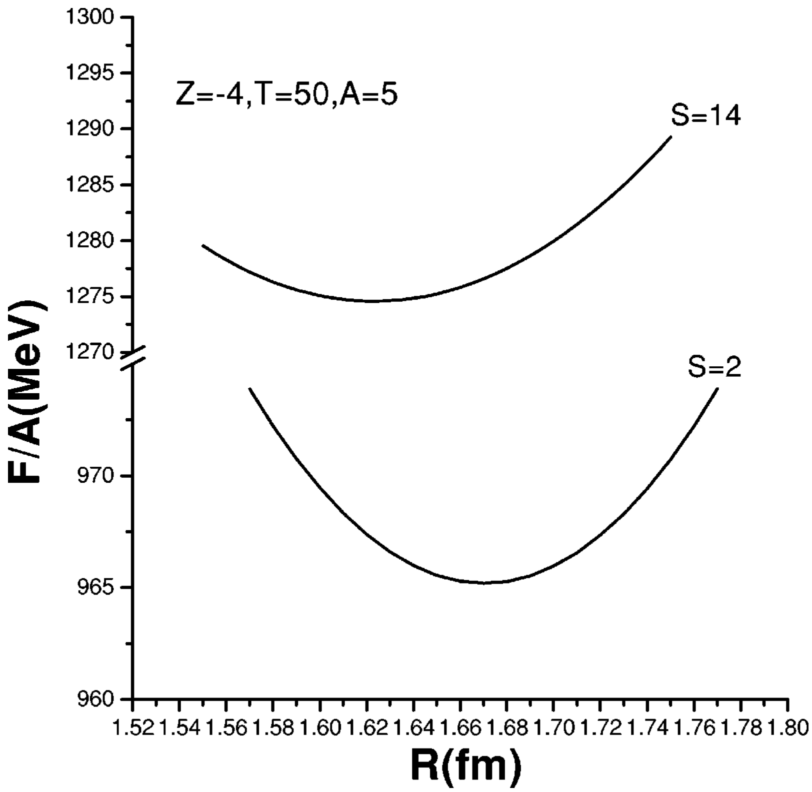

FIG. 6. The free energy per baryon F/A as functions of radius R with $A=5$, $Z=-4$, and $T=50$ MeV; the two lines represent the strangeness number $S=2$ and 14, respectively.

figures connect the masses of the nucleon, Λ, Ξ, and Ω. As a first cut for potential candidates of stable strangelets, those lying above this line can (or probably will) completely decay to the pure hadron state via strong processes, and only those beneath the line will be possible for metastable or stable strangelets [8].

We consider the influence of temperature now. As shown in the last section, the free energy per baryon increases when temperature decreases. The positions of the dots will increase and many dots will cross the line and become unstable when temperature decreases. Figure 11 shows this result clearly. Figure 11 is the same as Fig. 9 except for temperature T

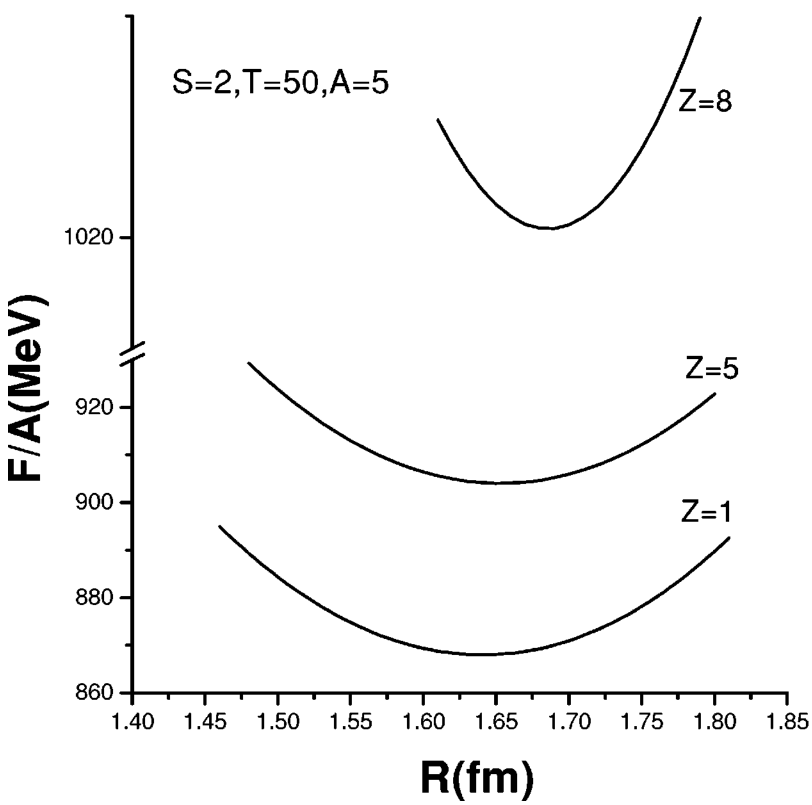

FIG. 7. The free energy per baryon F/A as functions of radius R with $A=5$, $S=2$, and $T=50$ MeV; the three lines represent the electric charge $Z=1$, 5, and 8, respectively.

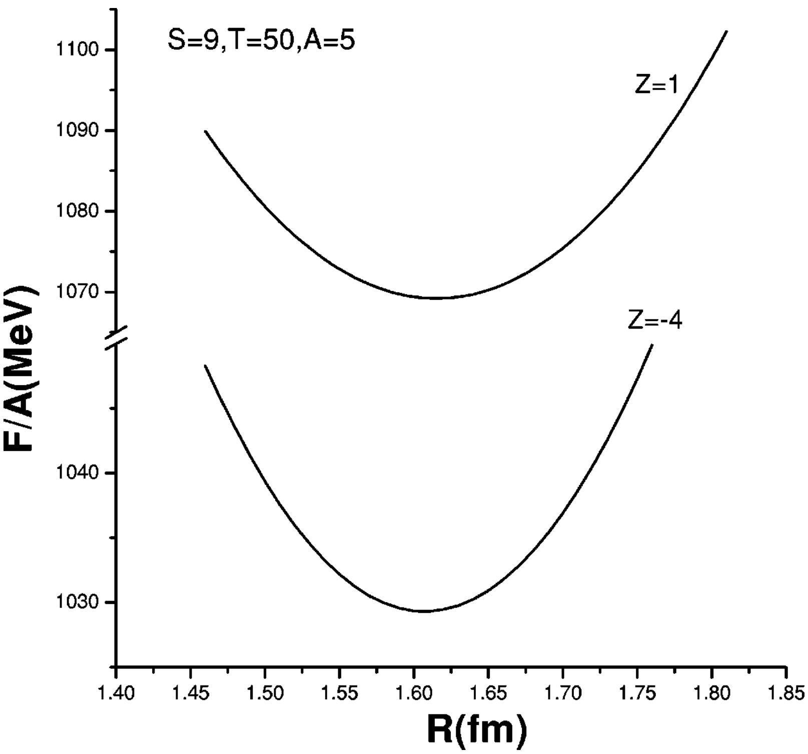

FIG. 8. The free energy per baryon F/A as functions of radius R with $A=5$, $S=9$, and $T=50$ MeV; the two lines represent the electric charge $Z=-4$ and 1, respectively.

$=20$ MeV. Comparing these two figures, we find many dots across the line when temperature decreases from 50 to 20 MeV. At low temperature, more strangelets can decay to the pure hadronic state by the strong process.

Here we must emphasize that although any strangelet initially formed in this process cannot decay to a pure hadron state, it is still possibly unstable because it can decay to a hadron and another strangelet with change in baryon number, strangeness number, and charge [8]. We will look for possible strong decays, i.e., single baryon $\{n, p, \Lambda, \Sigma^+, \Sigma^-, \Xi^0, \Xi^-$, and $\Omega\}$ emission and mesonic decays at the finite size configuration at finite temperature.

The baryon number A, strangeness number S, and electric charge Z are conserved in the strong process. A general expression of a strong baryon decay for a strangelet $Q(A,S,Z)$ can be written as

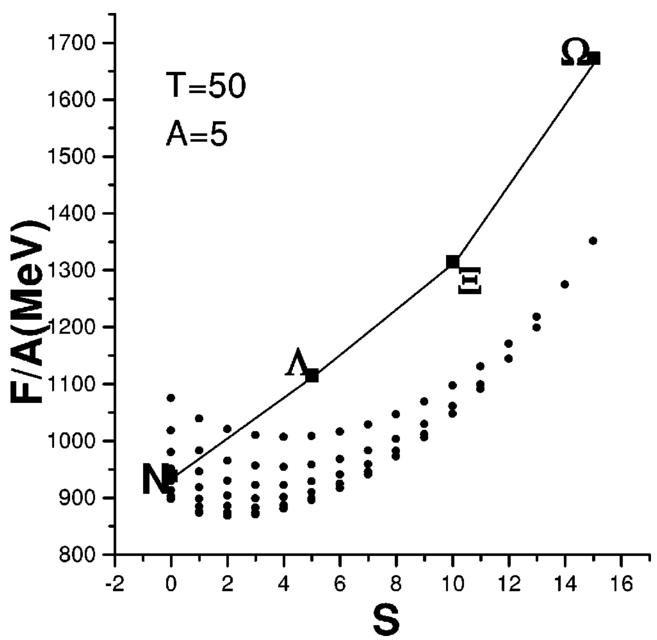

FIG. 9. The dots stand for the free energy per baryon F/A with various strangeness numbers S for all possible strangelets with baryon number $A=5$ at temperature $T=50$ MeV. The masses of the nucleon, Λ, Ξ, and Ω, are represented by the filled squares, respectively.

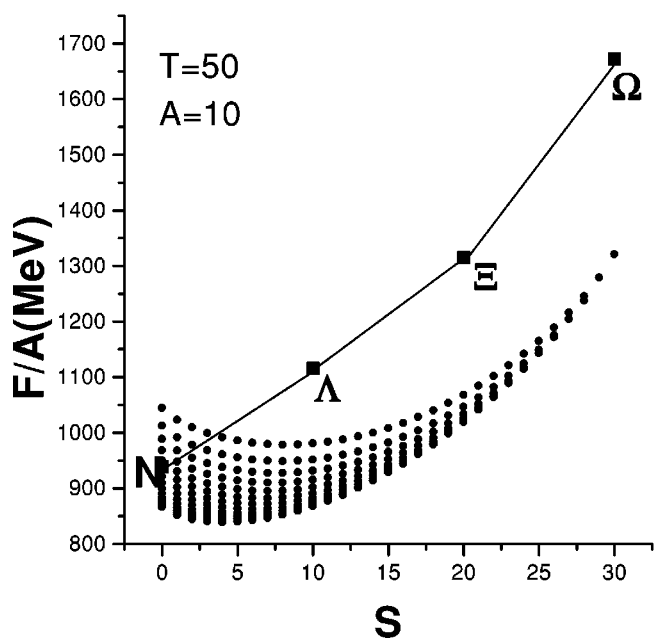

FIG. 10. The same as Fig. 9, but for baryon number $A=10$.

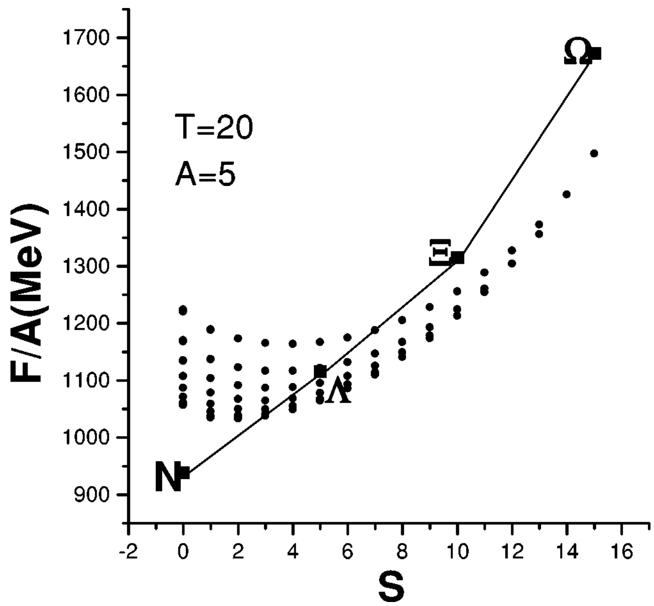

FIG. 11. The same as Fig. 9, but for temperature $T=20$ MeV.

$$Q(A,S,Z)\rightarrow Q(A-1,S-S_x,Z-Z_x)+x(1,S_x,Z_x). \tag{33}$$

And this process is allowed if the free energy balance of the corresponding reaction is

$$F(A,S,Z)>F(A-1,S-S_x,Z-Z_x)+m_{x,} \tag{34}$$

where F stands for the total free energy of the strangelet and x stands for a baryon with strangeness number S_x and electric charge Z_x. Our results of numerical calculation are shown in Figs. 12–14. For $A=5$ and $T=50$ MeV, all strangelets including those lying above the lines of Fig. 9 and those that satisfy the inequality (34) are depicted as circles in Fig. 12. These strangelets undergo strong decay and are unstable. The unstable strangelets for $A=10$ and $T=50$ MeV are drawn by circle in Fig. 13. Figures 12 and 13 show that the strangelets with small strangeness number S and situated in the left side of the figure are unstable.

To study the temperature effect, the same figure for $A=5$ and $T=20$ MeV are shown in Fig. 14. Comparing Figs. 12 and 14, we find that many strangelets become unstable when temperature decreases. A lower temperature favors the strong decay of the strangelet.

B. Weak decay and metastable strangelets

According to the definition of Schaffner-Bielich *et al.* [8], "a strangelet is called metastable in the following if its energy lies under the corresponding (free) hadronic matter of the same baryon number, charge, and strangeness, and if it cannot emit a single hadron or multiple hadrons by strong processes." At finite temperature, instead of energy, we use free energy. A metastable strangelet can then only decay via weak processes such as the nonleptonic (hadronic) decays. In this subsection, we study all possible weak hadronic decay for metastable strangelets.

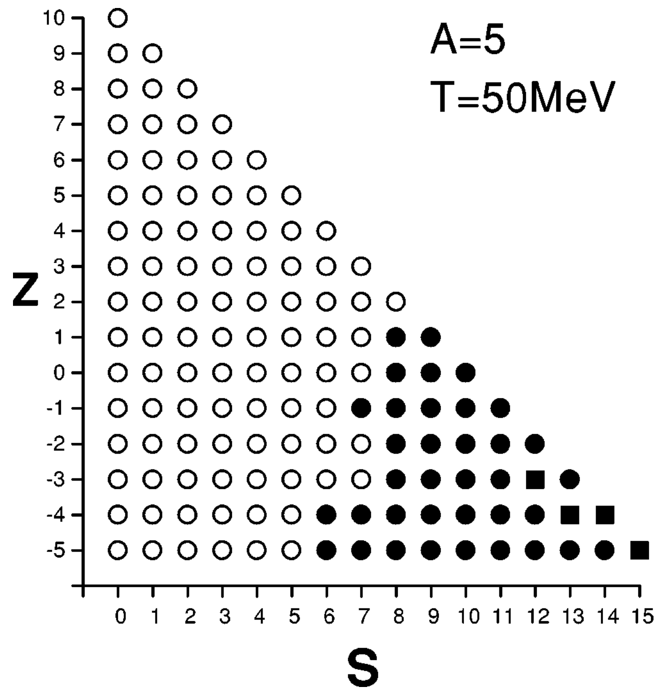

FIG. 12. The electric charge Z as a function of the strangeness number S for unstable strangelets (open circles), metastable strangelets (filled circles), and stable strangelets (filled squares) with baryon number $A=5$ at temperature $T=50$ MeV.

In the weak process, the baryon number A and the electric charge Z are conserved, but the strangeness number S is not conserved. For the weak decay, $\Delta S=\pm 1$. Therefore, a general expression of a weak baryon decay for a strangelet $Q(A,S,Z)$ can be written as

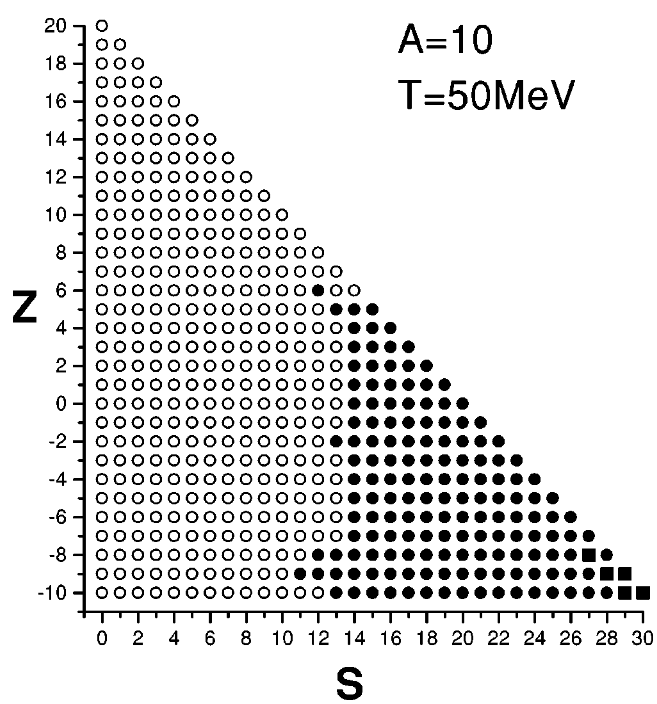

FIG. 13. The same as Fig. 12, but for baryon number $A=10$.

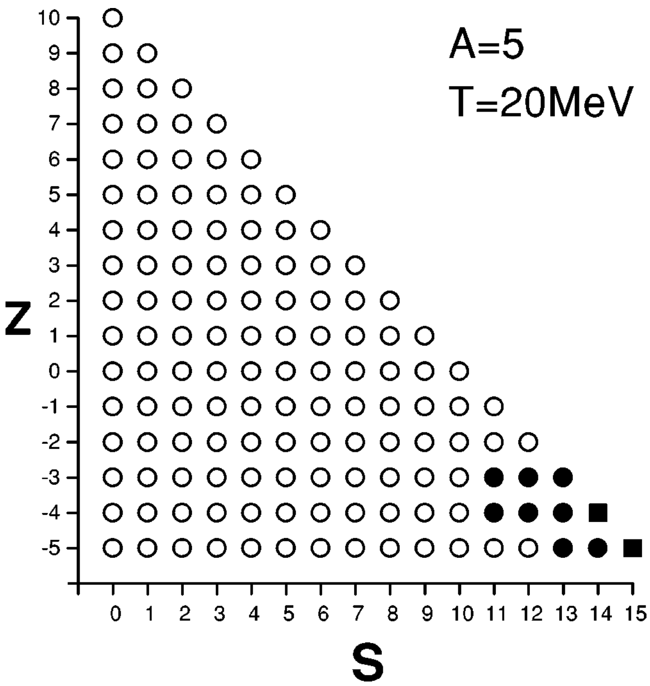

FIG. 14. The same as Fig. 12, but for temperature $T=20$ MeV.

$$Q(A,S,Z)\rightarrow Q(A-1,S-S_x-1,Z-Z_x)+x(1,S_x,Z_x). \quad (35)$$

This process is allowed if the free energy balance of the corresponding reaction is

$$F(A,S,Z)>F(A-1,S-S_x-1,Z-Z_x)+m_{x}. \quad (36)$$

The metastable strangelets that satisfy the inequality (36) are shown in Figs. 12, 13, and 14 with filled circle. We find that they are almost always situated in the area with negative charge (or slightly positive charge) and high strangeness number. In particular, high strangeness favors the stability of strangelet. As shown in Figs. 12–14, a minimal strangeness S_c above which ($S>S_c$) strangelets are metastable or stable exists. The values of the minimal strangeness S_c are 5 in Fig. 12 ($A=5$, $T=50$ MeV) and 10 in Fig. 13 ($A=10$, $T=50$ MeV). Defining the strangeness fraction f_s as

$$f_s=\frac{S}{A}, \quad (37)$$

Schaffner-Bielich *et al.* had predicted that there exists a critical f_{sc} at zero temperature and pointed that the metastable or stable strangelets could only be found above this value $f_s>f_{sc}$. Our results strongly support their prediction and extend it to finite temperature. We obtained $f_{sc}=1$ at $T=50$ MeV. This value does not depend on the baryon numbers. But as shown in Fig. 14, f_{sc} depends on the temperature. It becomes $f_{sc}=\frac{10}{5}=2$ at $T=20$ MeV.

Now we turn to discuss the charge dependence of the stability of strangelet. As shown in Figs. 12–14, higher negative charge favors metastable and/or stable strangelets. A maximal charge, which is $Z_m=1$ in Fig. 12 ($A=5$, $T=50$ MeV), $Z_m=6$ in Fig. 13 ($A=10$, $T=50$ MeV) and $Z_m=-3$ in Fig. 13 ($A=5$, $T=20$ MeV), exists. The strangelets would be stable or metastable when $Z\leqslant Z_m$. Defining charge fraction f_z as

$$f_z=\frac{Z}{A}, \quad (38)$$

we find that the maximal charge fraction depends on not only the temperature but also the baryon number A. For example, f_{zm} equals $\frac{1}{5}$ for $A=5$ and $\frac{6}{10}$ for $A=10$ when $T=50$ MeV.

C. Stable strangelets

The strangelet that is stable against both strong and weak decay is called a stable strangelet. The stable strangelets are shown in Figs. 12–14 by filled squares. We find that only a few strangelets cannot decay via strong and weak reactions and be completely stable. For example, as shown in Fig. 12, for $A=5$ and $T=50$ MeV, in total 128 strangelets, only 4 strangelets are stable $Z=-3,S=12$; $Z=-4,S=13$; $Z=-4,S=14$; and $Z=-5,S=15$.

Finally, we hope to emphasize that the high negative charge and the high strangeness number favor the stable strangelets obviously at finite temperature. The stable strangelets in Figs. 12–14 are all highly negative charged. The conclusion given by Schaffner-Bielich *et al.* at zero temperature [8] is still correct at finite temperature.

V. SUMMARY AND DISCUSSION

In summary, by using the QMDTD model, we have studied the thermodynamical properties and the stability of strangelets at finite temperature. We obtain the following results.

(1) For fixed strangeness and charge, free energy per baryon decreases as the temperature increases. The stable radius of the strangelet decreases when the strangeness increases or the charge decreases.

(2) The higher temperature favors the stability of the strangelets. Comparing Fig. 12 with Fig. 14, we see clearly that the total area of metastable and stable strangelets expands when the temperature increases. But this result must be readdressed at very high temperature. The reason is that we use m_x to represent the free energy of the baryon in inequalities (34) and (36). This approximation neglects the quark structure of the baryon and treats the baryon as a single particle, and then its entropy can be omitted. At high temperature, the entropy of the quark cluster (i.e., baryon) must be considered.

(3) The higher negative charge and higher strangeness number favor the stability of the strangelets. The stable strangelets are highly negatively charged and have high strangeness.

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[1] S.A. Bass, M. Gyulassy, H. Stöcker, and W. Greiner, J. Phys. G **25**, R1 (1999), and references herein.

[2] J. Barrette *et al.*, Phys. Lett. B **252**, 550 (1990); M. Aoki *et al.*, Phys. Rev. Lett. **69**, 2345 (1992); K. Borer *et al.*, *ibid.* **72**, 1415 (1994); D. Beavis *et al.*, *ibid.* **75**, 3078 (1995); T. Armstong *et al.*, *ibid.* **79**, 3612 (1997); G. Appleqvist *et al.*, *ibid.* **76**, 3907 (1996).

[3] For example, see B. Zhang, C.H. Ko, B.A. Li, Z. Lin, and B.H. Sao, Phys. Rev. C **62**, 054905 (2000).

[4] C. Greiner, P. Koch, and H. Stöcker, Phys. Rev. Lett. **58**, 1825 (1987); Phys. Rev. D **44**, 3517 (1991).

[5] E. Farhi and R.L. Jaffe, Phys. Rev. D **30**, 2371 (1984).

[6] M.S. Berger and R.L. Jaffe, Phys. Rev. C **35**, 213 (1987).

[7] E.P. Gilson and R.L. Jaffe, Phys. Rev. Lett. **71**, 332 (1993).

[8] J. Schaffner-Bielich, C. Greiner, A. Diener, and H. Stöcker, Phys. Rev. C **55**, 3038 (1997).

[9] Y. Zhang and R.K. Su, Phys. Rev. C **65**, 035202 (2002).

[10] Y. Zhang, R.K. Su, S.Q. Ying, and P. Wang, Europhys. Lett. **56**, 361 (2001).

[11] G.N. Fowler, S. Raha, and R.M. Weiner, Z. Phys. C **9**, 271 (1981).

[12] S. Chakrabarty, Nuovo Cimento Soc. Ital. Fis., B **106**, 1023 (1991); Phys. Rev. D **43**, 627 (1991); **48**, 1409 (1993).

[13] O.G. Benrenuto and G. Lugones, Phys. Rev. D **51**, 1989 (1995); G. Lugones and O.G. Benrenuto, *ibid.* **52**, 1276 (1995).

[14] G.X. Peng, H.C. Chiang, B.S. Zou, P.Z. Ning, and S.J. Luo, Phys. Rev. C **62**, 025801 (2000); G.X. Peng, H.C. Chiang, P.Z. Ning, and B.S. Zou, *ibid.* **59**, 3452 (1999).

[15] P. Wang, Phys. Rev. C **62**, 015204 (2000).

[16] Y. Zhang, W.L. Qian, S.Q. Ying, and R.K. Su, J. Phys. G **27**, 2241 (2001).

[17] R. Balian and C. Block, Ann. Phys. (N.Y.) **60**, 401 (1970).

[18] T.H. Hanssan and R.L. Jaffe, Phys. Rev. D **35**, 213 (1987).

[19] J. Madsen, Phys. Rev. D **47**, 5156 (1993); **50**, 3328 (1994).

[20] Y.B. He, C.S. Gao, X.Q. Li, and W.Q. Chao, Phys. Rev. C **53**, 1903 (1996).

[21] R. Mattiello, C. Hartnark, A.V. Keitz, J. Schaffner, H. Sorge, H. Stöcker, and C. Greiner, Nucl. Phys. B, Proc. Suppl. **24B**, 221 (1991).

[22] L. Gerland *et al.*, in *Proceedings of the International Conference on Relativistic Aspects of Nuclear Physics*, edited by T. Kodoma *et al.* (World Scientific, Singapore, 1996).