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CHARACTERISTICS OF FREE SURFACE OF HOT STRANGE QUARK MATTER

A. G. ALAVERDYAN *

Chair of Wave Processes Theory and Physics YSU, Armenia

Within the framework of MIT bag model, properties of hot strange quark matter at zero pressure are investigated. It is shown that the self-boundness property of strange quark matter has a temperature dependent character. With increasing temperature, the strange quark matter which is self-bound at zero temperature, starting with a certain critical temperature becomes not self-bound.

***Keywords*:** hot quark matter, strange star, free surface.

Introduction. It is known that during compression, the ordinary baryonic matter turns to a continuous quark matter through the phase transition. Such a matter consists of u, d, s quarks and leptons which neutralize electric charges of quarks. Due to the presence of strange quark, this matter is called strange quark matter (SQM) [1]. Since there is no a fully reliable theory for the description of quark matter phase, we considered strange quark matter within the MIT bag model [2]. In the MIT bag model the quarks are assumed to be confined to a finite region of space, in the so-called "bag", by a vacuum pressure B. The pressure from the quarks inside the bag is provided by the Fermi pressure and interactions between quarks is determined in the one-gluon exchange approximation corresponding to the first order of strong interaction coupling constant $\alpha_c = g^2/4\pi$, where g is the QCD coupling constant [3]. Values of model parameters B, α_c and masses of quarks are chosen such a way to well describe the properties of hadrons. Unfortunately, only regions of possible values for the mentioned parameters are determined. Masses of u and d quarks do not exceed 10 MeV, meanwhile Fermi energies of quarks in SQM exceed 300 MeV. Therefore, in our model the u- and d- quarks are considered to be massless. As a region of possible values for m_s, $90-200\,MeV$ is accepted. The value of the current strange quark mass, as was reported by the Particle Data Group, is $95\pm5\,MeV$ [4]. Meanwhile, for the strange quark matter in the stellar interior another (constituent) mass of the strange quark is "observed". Accordingly, in the present work we conducted numerical calculations for the three values of the strange quark mass $m_s:\{95;125;150\}MeV$. Possible values for the parameter B underlie in the interval of $40-100\ MeV/fm^3$. Regardless of the values for parameters B, α_c, and m_s, the energy of hot strange quark matter (HSQM) per baryon number ε, always at a certain concentration of the baryon number $n = n_0$ has a local minimum ε_{min}. If $\varepsilon_{min} < m_n c^2$, where m_n is the neutron mass, and c is the speed of light, then SQM is self-bound state of matter. Otherwise, if $\varepsilon_{min} < M(^{56}\mathrm{Fe})/56$, then SQM is the true ground state of matter. Celestial bodies consisting of solely such matter are called strange stars [1]. Strange stars have a distinct surface. On the

* E-mail: anialaverdyan@ysu.am

surface of such object, the concentration abruptly falls from the value n_0 to zero. The present paper is devoted to the investigation of hot strange matter at $n = n_0$.

Basic Equations for Chemical Equilibrium in HSQM. In the ordinary matter at the temperature $kT \sim m_e c^2$ (k is Boltzmann constant, m_e is electron mass, c is speed of light in vacuum) electron-positron pairs are produced. Plasma frequency ω_p in SQM is such that $\hbar\omega_p \sim 20\ MeV$ [5] ($\hbar$ is Planck constant). In the thermal spatial field HSQM the quants with an energy less than $\sim 20\ MeV$ are absent. On the other hand, electrons in HSQM are quasi-degenerate, therefore, only layers with an energy of order $10-20\ MeV$ are filled (this is exactly the Fermi-energy of electrons in SQM). Therefore, the electron-positron pairs are capable to generate only photons with an energy $\sim 20\ MeV$ and greater.

Assuming that an ordinary star matter was turned to HSQM whit the explosion of supernova star, the temperature HSQM may achieve values $T \approx 10^{12} K$ ($kT \approx 100\ MeV$). Duration of such a high temperature stage is negligible with respect to the star lifetime. Anyway, there are some issues that cannot be addressed without investigation of that stellar evolution stage. One of them is the maximum value for the mass of cold strange stars. This issue is discussed in [6].

The thermodynamic equilibrium state of HSQM is determined by conditions:

1. β-equilibrium: $\mu_d = \mu_s = \mu_u + \mu_{e^-}$.
2. Equilibrium of electron-positron pairs: $\mu_{e^-} = -\mu_{e^+}$.
3. Electrical neutrality: $\frac{2}{3}\, n_u - \frac{1}{3}\,(n_d + n_s) - n_{e^-} + n_{e^+} = 0$.
4. Baryon number conservation law: $n = \frac{1}{3}\,(n_u + n_d + n_s)$.

Here μ_i stands for the chemical potential, meanwhile n_i is the concentration of $i^{\,th}$ type of particle, where $i = u,\ d,\ s,\ e^+,\ e^-$. Electrons and positrons in HSQM stand for an ideal Fermi gas. With approximation $\alpha_c = 0$ quarks also stand for such particles. In the present paper the numerical calculations are performed within the framework of the such approximation. Relation between the chemical potential μ_i, the concentration of particle n_i and the temperature T is given by the formula:

$$n_i = \frac{g_i}{2\pi^2}\int\limits_0^\infty \frac{p^2 dp}{exp[\varepsilon_i(p) - \mu_i]/kT + 1}, \tag{1}$$

where $i = u,\ d,\ s,\ e^-,\ e^+$; $\varepsilon_i(p) = \sqrt{m_i c^4 + p^2 c^2}$; g_i is degeneracy factor of the particle i (2 for the leptons, 6 for the quarks). For quasi-degenerate quarks, the thermal corrections to thermodynamic quantities are considered in the approximation of $(kT/\mu)^2$ [7, 8]. Although leptons are ultra-relativistic, however, this approximation is not applicable to them. Therefore, in numerical calculations for such particles, exact integral expressions are used. The strange quark mass is considered in the approximation of $(m_s c^2/\mu)^2$. For a given value of the baryon number density and T, the conditions $(1-4)$ and Eq. (1) determine the chemical potentials and the concentration of all particles. For solving these equations the method from [9] was used.

Characteristics HSQM at Zero Pressure. If SQM is self-bound, then the condition $P(n,T) = 0$ identifies the concentration of baryon number n_0 and all the thermodynamic characteristics on the free surface of the substance at the T. Otherwise, the characteristics of HSQM are defined in the vicinity of the phase equilibrium point with baryonic matter [10].

Numerical computations are carried out for the values of MIT bag model parameters, namely, $B = \{40;\ 60;\ 80\}\ MeV/fm^3$, $m_s = \{95;\ 125;\ 150\}\ MeV$ and $\alpha_c = 0$.

The results of the calculations are shown in Fig. 1–5.

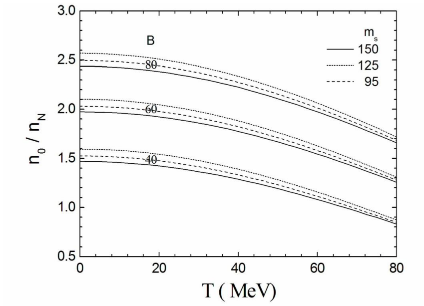

Fig. 1. Temperature dependence of baryon number density n_0 at surface of bare strange star in units of normal nuclear number density $n_N = 0.15\,fm^{-3}$ for different values of model parameters B and m_s.

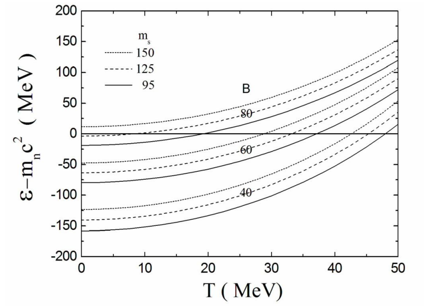

Fig. 2. Energy per baryon $\varepsilon(n_0, T)$ for SQM at zero pressure as a function of temperature for different values of model parameters B and m_s.

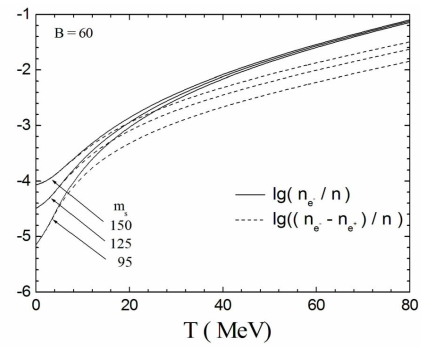

Fig. 3. Electron fraction parameter $\log(n_{e^-}/n)$:
Solid lines. For SQM at zero pressure as a function of temperature for B=60 MeV/fm^3 and different values of m_s.
Dashed lines. For electron-positron fraction difference parameter $\log(n_{e^-}/n - n_{e^+}/n)$.

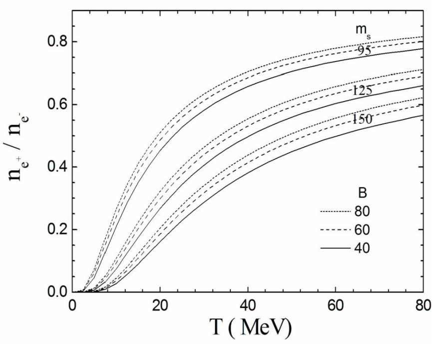

Fig. 4. Temperature dependence of positron to electron ratio $n_{e^-}/n - n_{e^+}/n$. n_{e^+}/n_{e^-} at zero pressure for different values of model parameters B and m_s.

Fig. 1 shows the temperature dependence of baryon number density n_0/n_N at surface of bare strange star for different values of model parameters B and m_s ($n_N = 0.15\,fm^{-3}$ is the normal nuclear density). As expected, the higher the temperature HSQM, the lower the density of the quarks. With increasing temperature, the thermal corrections to the pressure increase. Therefore, at a constant pressure, the higher the temperature, the lower the quark concentration. With increasing temperature, the value n_0 at the free surface approaches the value of normal nuclear density n_N. This should be treated with caution. Indeed, as in Fig. 2 is shown the value $\Delta\varepsilon = \varepsilon(n_0, T) - m_n c^2$ increases with increasing temperature and becomes positive. That is, self-boundness of HSQM is violated. Therefore, if the cold SQM cannot be in thermodynamic equilibrium with the ordinary baryonic matter [11], then at a certain temperature, it may be possible. Fig. 2 shows that the smaller the possible value of B, the higher the critical temperature value corresponding to the violation of self-boundness. Calculations show that with increasing temperature of HSQM, the amount of leptons increases dramatically. Fig. 3 shows the temperature dependencies of n_{e^-}/n_0 and $(n_{e^-} - n_{e^+})/n_0$ at $P = 0$ for $B = 60\,MeV/fm^3$ and $m_s = \{95;\ 125;\ 150\}\,MeV$.

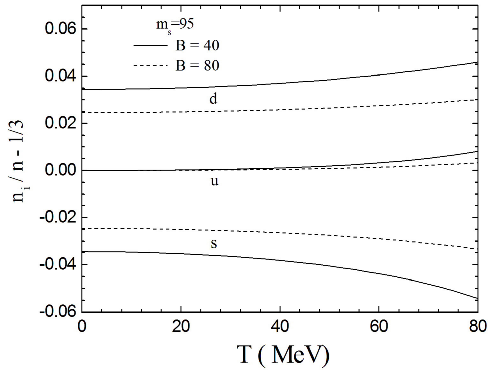

Fig. 5. Temperature dependencies for the relative deviations of number densities of $u,\ d,\ s$ quarks from the symmetric value $1/3$.

If in cold SQM the number of electrons by $4-5$ orders of magnitude is smaller than the number of quarks, then at temperature $kT = 80\ MeV$, we have $n_{e^-} \approx 0.1n_0$. At first glance it may seem that such an abrupt increase in the number of electrons must be accompanied by a similar increase in the asymmetry in the number of different types of quarks. However, this does not happen, because the chemical potential of the electrons with increasing temperature changes slightly, though their number increases so strongly. The reason for this is very simple. Firstly, only a portion of these electrons neutralize the charge of the quarks. Secondly, with increasing temperature, electron gas ceases to be degenerated. On one hand, increasing the number of electrons should lead to an increased degeneration and, on the other hand, the change of electron gas in the direction of Boltzmann gas prevents an increase of chemical potential of the electrons. The last factor is dominant, and the chemical potential of the electrons does not exceed $10-20\ MeV$. Even with $kT = 80\ MeV$, the number of electrons is an order of magnitude smaller than the number of quarks. Fig. 4 shows the temperature dependence of the ratio n_{e^+}/n_{e^-}. It is clear that in case of $kT = 80\ MeV$, the number of electrons $n_{e^-} - n_{e^+}$ which provide electro neutrality, constitute $\{19;\ 29;\ 38\}$ percents of the total number of electrons for $B = 80\ MeV/fm^3$ and $m_s = \{95;\ 125;\ 150\}\ MeV$, respectively.

Fig. 5 shows temperature dependencies for the relative deviations of concentrations of $u,\ d,\ s$ quarks from the symmetric value $1/3$ ($n_i/n_q - 1/3$). Deviation from symmetry in case of $T = 0$ is due to the presence of non zero strange quark mass. This deviation increases with increasing temperature; meanwhile the deviation for s quarks is more than for d quarks. Number of u quarks changes relatively little.

Conclusion. Numerical calculations within the framework of MIT bag model show that on the free surface of HSQM ($P = 0$), the following assertions hold:

∘ with increasing temperature, the relative numbers of u and d quarks are increased, meanwhile, the relative numbers of s quarks are decreased;

∘ the more the temperature of HSQM, the smaller the concentration of quarks n_0. With higher temperature $kT \approx 60-80\ MeV$, the baryon number density approaches the value of normal nuclear density n_N;

∘ energy per baryon of HSQM sufficiently strong depends on the temperature. Being self-bounded at temperature $T = 0$ SQM becomes non self-bounded when temperature increases. Therefore, for definite possible values of parameters for MIT bag model, non self-bound hot strange quark matter during cooling may be self-bound. Therefore, the hot hybrid neutron star with a cooling becomes a strange quark star with the outer shell. The substance of this shell will consist of atomic nuclei and a degenerate electron gas [12];

◦ the number of electrons in HSQM can reach 10 percent from the number of quarks. Despite this, the chemical potential of the electrons does not exceed the value of $10-20\,MeV$;

◦ despite the abrupt increase in the number of electrons, with increasing temperature, relative changes in the concentration of quarks from the values at $T=0$, are negligible.

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