
Structure of spin polarized strange quark star in the presence of magnetic field at finite temperature

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Abstract

In this paper, the thermodynamic properties of spin polarized strange quark matter at finite temperature in the presence of a strong magnetic field using MIT bag model have been calculated. We have also computed the equation of state of spin polarized strange quark matter in the presence of strong magnetic field and finally, using this equation of state, the structure of spin polarized strange quark star at different temperatures and magnetic fields has been investigated.

Keywords: Quark matter; quark star; structure; finite temperature

1. Introduction

One of the interesting features of the compact objects is the strange quark star (SQS) composed of the strange quark matter (SQM). The composition of SQS was first proposed by Itoh [1]; simultaneously with formulation of Quantum chromo dynamics (QCD). Later, Bodmer discussed the fate of an astronomical object collapsing to such a state of matter [2]. The perturbative computations of the equation of state of the SQM was developed after the formation of QCD, but the region of validity of these calculations was restricted to very high densities [3]. The concept of SQS was also discussed by Witten. He proposed that SQM is composed of light quarks, and is more stable than the nuclei [4]. Therefore the SQM can be the ground state of matter. With this point of view, other authors proposed the concept of SQS. The SQM is composed of 3-flavors of quarks (up, down and strange) and a small number of electrons to ensure the charge neutrality [5, 6]. A typical electron fraction is less than 10^{-3} (fm^{-3}) and it decreases from the surface to the center of SQS.

The collapsing star of a supernova will turn into a neutron star only if its mass is about $1.4 - 3 M_{\text{sun}}$. After formation of the neutron star, if the density of the core is high enough (10^{15} gr/cm^3) the nucleons dissolve to their components, quarks, and a hybrid star (neutron star with a core of SQM) is formed. But if after the explosion of supernova, in the stage

of proto-neutron, the if density of the core is high enough (10^{15} gr/cm^3), the pure SQS may be formed directly, making a quark-novae. If after collapse the leftover is more than $3M_e$ mass the star will be transformed to a black hole. For a neutron star, the radius decrease with mass, or in other words $M \propto 1/R$; while for an SQS, the mass-radius relation is $M \propto R^3$. Some results of observations show that for a typical SQS, the mass is more than $2.1 \pm 0.28 M_{\text{sun}}$ and the radius is more than 13.8 ± 1.8 [7]. Besides, recent observations indicate that objects RX J185635-3754 and 3C58 may be SQS [8].

The maximum magnetic field on the surface of magnetars is about 10^{15} G , however the highest possible magnetic field in the center of SQS that was estimated by virial theorem is between $10^{18} - 10^{20} \text{ G}$ [9, 16]. Therefore, investigating the effect of a strong magnetic field on the SQM properties is important in astrophysics. Some studies that investigate the effect of magnetic field on quark star and quark matter are available. Chakrabarty [17] studied the effects of a strong magnetic field on quark matter. He showed that the equation of state of SQS changes significantly in the presence of strong magnetic fields. Anand et.al. [18] expressed that the maximum mass, the radius and gravitational red-shift of the SQS increase as a function of the magnetic field.

Recently, we have calculated the structure of polarized SQS at zero temperature [19] and unpolarized SQS at finite temperature [20]. We have also calculated the structure of the neutron star

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with the quark core at zero temperature [21] and at finite temperature [22]. In this paper we calculate some properties of polarized SQS at finite temperature in the presence of a strong magnetic field. The plan of this work is as follows. In section 2, the energy and equation of state of SQM by the MIT bag model at finite temperature in the presence of a strong magnetic field is calculated and in section 3, we present the results of our calculations for different temperatures and magnetic fields.

2. Calculation of energy and equation of state of strange quark matter

The equation of state plays an important role in obtaining the structure of a star. There are different statistical approaches for calculation of the equation of state of quark matter (SQM) and all of them are based on the QCD, for example, the MIT bag model [23, 24], NJL model [25, 26] and perturbation QCD model [27, 28]. In this paper the equation of state of SQM by MIT bag model with the bag constant $B=90 \text{ MeV}/\text{fm}^3$ is calculated. The MIT bag model considers free particles confined to a bounded region by a bag pressure B . This pressure depends on the quark-quark interaction [29]. In other words, the bag constant (B) is the difference between the energy densities of the noninteracting quarks and the interacting ones. For the bag constant in the MIT bag model, different values such as 55 and $90 \text{ MeV}/\text{fm}^3$ are considered.

To obtain the equation of state of SQM, at first, the total energy of the system should be calculated. We do this work using the MIT bag model with the bag constant $B=90 \text{ MeV}/\text{fm}^3$ in the next section.

2.1. Energy of spin polarized strange quark matter at finite temperature in presence of magnetic field

At densities high enough ($10^{15} \text{ gr}/\text{cm}^3$) the hadronic phase is allowed to undergo a phase transition to the strange quark matter phase. Strange quark matter consists of u , d and s quarks, as well as electrons in weak equilibrium;

$$d \rightarrow u + e + \bar{\nu}_e, \quad (1)$$

$$u + e \rightarrow d + \nu_e, \quad (2)$$

$$u + d \rightarrow u + s, \quad (3)$$

$$s \rightarrow u + e + \bar{\nu}_e \quad (4)$$

To calculate the energy of SQM, we need to know the quark densities in terms of the baryonic number density. To compute these densities, we use the beta equilibrium and charge neutrality conditions in the above reactions. The beta

equilibrium and charge neutrality conditions lead to the following relations for the chemical potentials and densities of relevant quarks,

$$\mu_d = \mu_u + \mu_e, \quad (5)$$

$$\mu_s = \mu_u + \mu_e, \quad (6)$$

$$\mu_s = \mu_d, \quad (7)$$

$$\frac{2}{3}n_u - \frac{1}{3}n_s - \frac{1}{3}n_d - n_e = 0, \quad (8)$$

where μ_i and n_i are the chemical potential and the number density of particle i respectively. It should be noted that because the neutrinos escape from the interior matter of star, the chemical potential of neutrinos vanishes ($\mu_{\nu_e} = \mu_{\bar{\nu}_e} = 0$). Therefore, we get the above relations between the chemical potentials [5, 6]. As was mentioned in the previous section, we consider the system as pure SQM and ignore the electrons ($n_e = 0$) [30, 31, 32], therefore Eq. (8) becomes

$$n_u = \frac{1}{2}(n_s + n_d). \quad (9)$$

Now, we want to calculate the energy of SQM in the presence of a strong magnetic field. Therefore, we consider the spin polarized SQM composed of the u , d and s quarks with up and down spins. We show the number density of spin-up quarks by n_i^+ and spin-down quarks by n_i^- . The parameter of polarization is defined by the following relation,

$$\zeta_i = \frac{n_i^+ - n_i^-}{n_i}, \quad (10)$$

where $0 \leq \zeta_i \leq 1$ and $n_i = n_i^+ + n_i^-$. The chemical potential μ_i for any value of the temperature (T) and number density (n_i), is calculated using the following constraint,

$$n_i = \sum_{P=\pm} \frac{g}{2\pi^2} \int_0^\infty f(n_i, k^{(p)}, T) k^2 dk, \quad (11)$$

where

$$f(n_i, k^{(p)}, T) = \sum_{P=\pm} \frac{1}{\exp\left(\beta((m_i^2 c^4 + \hbar^2 (k^{(p)})^2 c^2)^{\frac{1}{2}} - \mu_{eff})\right) + 1}, \quad (12)$$

is the Fermi-Dirac distribution function. In the above equation $\beta = 1/k_B T$ and g is degeneracy number of the system. In this equation μ_{eff} is the effective chemical potential in the presence of magnetic field. The effective chemical potential is equal to $\mu_i \mp \mu_s B$ where μ_s is magnetic moment and B is the magnetic field. In other words, the single particle energy is $\epsilon_i = \sqrt{m_i^2 c^4 + \hbar^2 k^p} \pm \mu_s B$.

The energy of spin polarized SQM in the presence of the magnetic field within the MIT bag model is as follows,

$$\varepsilon_{tot} = \varepsilon_u + \varepsilon_d + \varepsilon_s + \varepsilon_M + B, \quad (13)$$

where

$$\varepsilon_i = \sum_{P=\pm} \frac{g}{2\pi^2} \int_0^\infty (m_i^2 c^4 + \hbar^2 (k^{(P)})^2 c^2)^{1/2} f(n_i, k^{(P)}, T) k^2 dk, \quad (14)$$

here $k^\pm = (\pi^2 n_i)^{1/3} (1 \pm \zeta_i)^{1/3}$. In our calculations, we suppose that $\zeta = \zeta_u = \zeta_d = \zeta_s$. In Eq. (13), $\varepsilon_M = \frac{E_M}{V}$ is the magnetic energy density of SQM where $E_M = -M \cdot B$ is the magnetic energy. By considering a uniform magnetic field along z direction, the contribution of magnetic energy of the spin polarized SQM is given by

$$E_M = -\sum_{i=u,d,s} M_z^{(i)} B, \quad (15)$$

where $M_z^{(i)}$ is the magnetization of the system corresponding to particle i which is given by

$$M_z^{(i)} = N_i \mu_i \zeta_i. \quad (16)$$

In the above equation N_i and μ_i are the number density and magnetic moment of particle i . Finally, the magnetic energy density of SQM can be obtained by the following relation,

$$\varepsilon_M = -\sum_i n_i \mu_i \zeta_i B. \quad (17)$$

We obtain the thermodynamic properties of the system using the Helmholtz free energy,

$$F = \varepsilon_{tot} - T S_{tot}, \quad (18)$$

where S_{tot} is the total entropy of SQM,

$$S_{tot} = S_u + S_d + S_s. \quad (19)$$

In Eq. (19), S_i is entropy of particle i ,

$$S_i(n_i, T) = -\frac{3}{\pi^2} k_B \int_0^\infty f(n_i, k, T) \ln(f(n_i, k, T)) + (1 - f(n_i, k, T)) \ln(1 - f(n_i, k, T)) k^2 dk. \quad (20)$$

2.2. Equation of state of spin polarized strange quark matter

For deriving the equation of state of strange quark matter (SQM), the following equation is used,

$$P(n, T) = \sum_i (n_i \frac{\partial F_i}{\partial n_i} - F_i), \quad (21)$$

where P is the pressure of system, F_i is the free energy of particle i and n_i is the number density of particle i .

3. Result and discussion

3.1. Thermodynamic properties of spin polarized strange quark matter

In Fig. 1, we present the total free energy per volume versus the polarization parameter ζ , for $B = 5 \times 10^{18} G$, at different densities and temperatures. From Fig. 1, we can see that at each density and temperature, the energy is minimum at a particular value of the polarization parameter. This indicates that at each density and temperature, there is a meta stable state. We have found that for a fixed temperature, the polarization parameter corresponding to the meta stable state reaches zero by increasing the density. Similarly, we can see that at a fixed density, in the meta stable state the polarization parameter decreases by increasing the temperature. These results agree with those of reference [33].

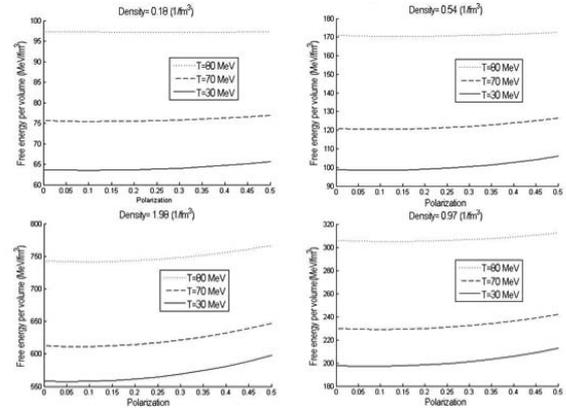


Fig. 1. Total free energy per volume as a function of the polarization parameter at different temperatures and densities for $B = 5 \times 10^{18} G$

In Fig. 2, the polarization parameter versus baryonic density has been plotted at different temperatures in the presence of magnetic field $B = 5 \times 10^{18} G$. We can see that the polarization parameter decreases by increasing the baryonic density. Fig. 2 shows that at a fixed density, the polarization parameter decreases by increasing the temperature. This is due to the fact that contribution of magnetic energy is more significant at low temperature.

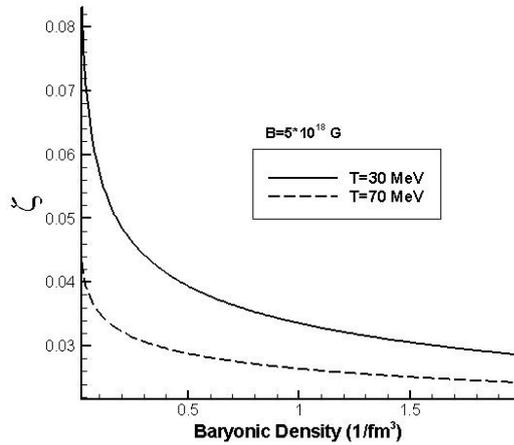


Fig. 2. The polarization parameter versus baryonic density at different temperatures for $B = 5 \times 10^{18} \text{ G}$

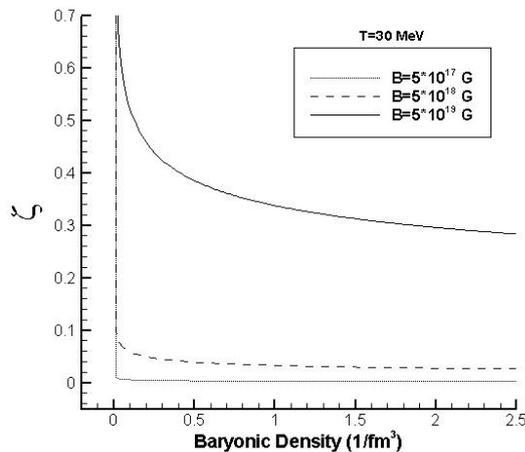


Fig. 3. The polarization parameter versus baryonic density at $T = 30 \text{ MeV}$ for different magnetic fields

The polarization parameter has also been drawn versus baryonic density at a fixed temperature ($T = 30 \text{ MeV}$) for different magnetic fields in Fig. 3. It is seen that for each density, the polarization parameter increases by increasing the magnetic field. As it can be seen from Fig.3, at high baryonic densities, for the magnetic fields lower than about $5 \times 10^{18} \text{ G}$ the polarization parameter becomes nearly zero. In other words, for lower magnetic fields at higher densities, the strange quark matter (SQM) becomes nearly unpolarized.

In Fig. 4, we have shown the polarization parameter as a function of the magnetic field for density $n = 0.5 \text{ fm}^{-3}$ at different temperatures. We can see that at lower values of the magnetic field, the polarization parameter is nearly zero, and at the magnetic fields greater than about $5 \times 10^{17} \text{ G}$, the polarization parameter increases as the magnetic field increases. Also, this figure shows

that for each value of the magnetic field, the polarization parameter increases by decreasing the temperature. This is because at the higher temperatures the contribution of the kinetic energy is higher compared to that of the magnetic energy.

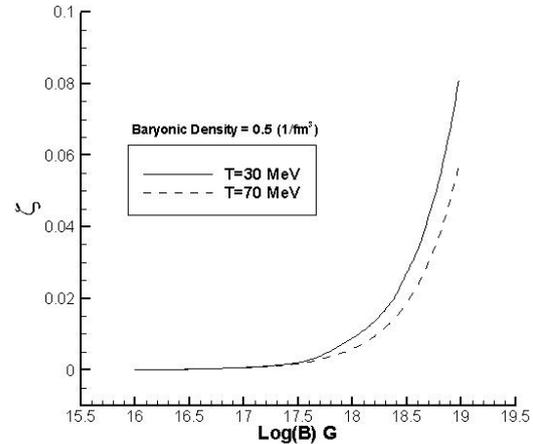


Fig. 4. The polarization parameter as a function of magnetic field at $n = 0.5 \text{ fm}^{-3}$ for different temperatures

We have shown the total free energy per volume of the spin polarized SQM as a function of the baryonic density in Fig. 5 for the magnetic field $B = 5 \times 10^{18} \text{ G}$ at different temperatures. From this figure, we have found that the free energy of the spin polarization SQM has positive values for all temperatures and densities. For each density, it is shown that the free energy decreases by increasing the temperature.

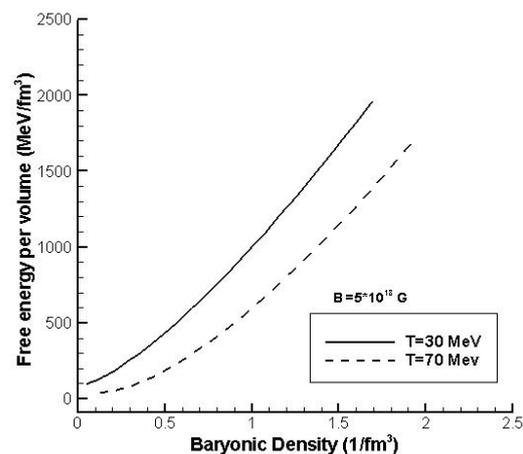


Fig. 5. The total free energy per volume of the spin polarized SQM as a function of the baryonic density for $B = 5 \times 10^{18} \text{ G}$ at different temperatures

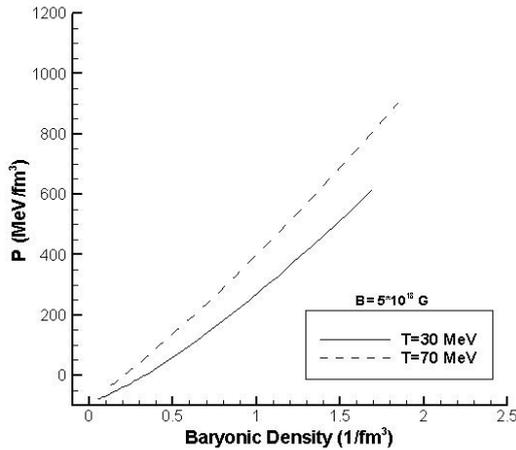


Fig. 6. The pressure of the spin polarized SQM for $B = 5 \times 10^{18} \text{ G}$ at different temperatures

The pressure of spin polarized SQM at different temperatures in the presence of magnetic field ($B = 5 \times 10^{18} \text{ G}$) has been plotted in Fig. 6. This figure shows that the pressure of SQM increases by increasing the density. We can also see that the pressure increases by increasing temperature. These results indicate that the equation of state of spin polarized SQM becomes stiffer by increasing the temperature.

3.2. Structure of spin polarized strange quark star

The structures of compact objects such as white dwarfs, neutron stars, pulsars and strange quark stars (SQS), are determined from the Tolman-Oppenheimer-Volkov equations (TOV) [34],

$$\frac{dP}{dr} = -\frac{G\left[\varepsilon(r) + \frac{P(r)}{c^2}\right]\left[m(r) + \frac{4\pi r^3 P(r)}{c^2}\right]}{r^2\left[1 - \frac{2Gm(r)}{rc^2}\right]}, \quad (22)$$

$$\frac{dm}{dr} = 4\pi r^2 \varepsilon(r). \quad (23)$$

Using the equation of state which was obtained in the previous section, we integrate the TOV equation to compute the structure of SQS.

In Fig. 7, the gravitational mass of spin polarized strange quark star (SQS) versus energy density at different temperatures for a magnetic field $B = 5 \times 10^{18} \text{ G}$ has been plotted. We can see that for all temperatures, the gravitational mass increases rapidly by increasing the energy density and finally reaches a limiting value (maximum gravitational mass). Fig. 7 shows that this limiting value decreases by increasing the temperature. From this result, we can conclude that the stiffer equation of state leads to the lower values for the gravitational mass of SQS.

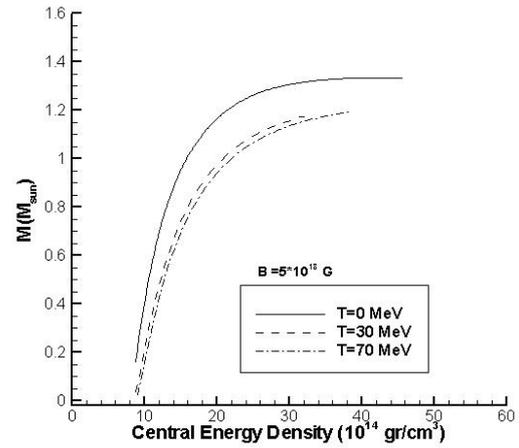


Fig. 7. The gravitational mass of spin polarized SQS versus energy density at different temperatures for $B = 5 \times 10^{18} \text{ G}$. The results of $T = 0 \text{ MeV}$ [19] have been also given for comparison

We have shown the gravitational mass of spin polarized SQS as a function of the radius at different temperatures in Fig. 8. This figure shows that the gravitational mass increases by increasing radius. We can see that the increasing rate of gravitational mass versus radius increases by increasing the temperature. According to Fig. 6, by increasing temperature, the equation of state becomes stiffer leading to the conclusion that by increasing temperature, mass and the radius of spin polarized SQS decrease. Fig. 9 shows the gravitational mass of SQS as a function of the energy density at a fixed temperature ($T = 30 \text{ MeV}$) for different magnetic fields. It can be seen that as the magnetic field increases, the rate of increasing of gravitational mass versus central energy density decreases, getting to a lower value at the limited case.

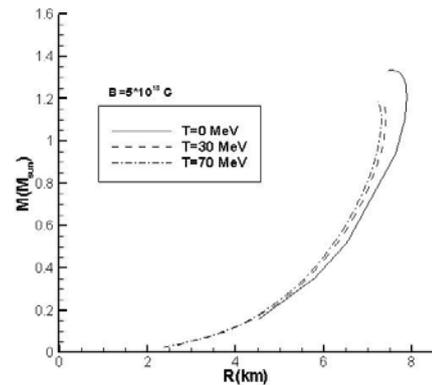


Fig. 8. The gravitational mass of spin polarized SQS as a function of the radius at different temperatures for $B = 5 \times 10^{18} \text{ G}$. The results of $T = 0 \text{ MeV}$ [19] have been also given for comparison

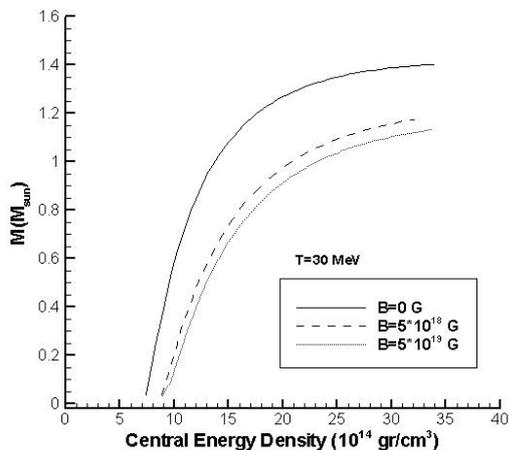


Fig. 9. The gravitational mass versus energy density at $T = 30 \text{ MeV}$ for different magnetic fields

In Table 1, we have shown the maximum mass and the corresponding radius of a spin polarized SQS at different temperatures for $B = 5 \times 10^{18} \text{ G}$. It is shown that by increasing the temperature, the maximum mass and radius of spin polarized SQS decreases. We have also shown the maximum mass and the corresponding radius of the spin polarized SQS for different magnetic fields at a fixed temperature $T = 30 \text{ MeV}$ in Table 2. We see that the maximum mass and radius of the spin polarized SQS decreases by increasing the magnetic field.

Table 1. Maximum mass and the corresponding radius of SQS for $B = 5 \times 10^{18} \text{ G}$ at different temperatures. The results of $T = 0 \text{ MeV}$ [19] have been also given for comparison

$T \text{ (MeV)}$	$M_{max} \text{ (} M_e \text{)}$	$R \text{ (km)}$
0	1.33	7.44
30	1.17	7.37
70	1.16	7.21

Table 2. Maximum mass and the corresponding radius of SQS for different magnetic fields at $T = 30 \text{ MeV}$

$B \text{ (G)}$	$M_{max} \text{ (} M_e \text{)}$	$R \text{ (km)}$
0	1.40	8.08
5×10^{18}	1.17	7.37
5×10^{19}	1.16	7.16

One of the method used to compare the mass and radius in our calculation with the observational values is calculation of the surface red-shift value. The maximum surface red-shift calculated in our work is $z_s = 0.38$ (for $T = 30 \text{ MeV}$ $B = 5 \times 10^{19} \text{ G}$) that is 55.34 lower than the upper bound on the surface red-shift for sub-luminal equation of states (i.e. $z_s^{CL} = 0.8509$). Furthermore, the

minimum amount of red-shift in our calculations is equal to $z_s = 0.37$, which is almost near the red-shift of RX J185635-3754, that is $z_s = 0.35 \pm 0.37$.

4. Summary and Conclusions

In this paper, the thermodynamic properties of the strange quark matter (SQM) composed of the spin-up and spin-down of the up, down and strange quarks at finite temperature in the presence of an strong magnetic field using the MIT bag model was investigated. We computed the total free energy of the spin polarized SQM at finite temperature in the presence of a strong magnetic field. We found that the free energy reaches a minimum at a particular value of the polarization parameter showing a meta-stable state. We have also shown that the polarization parameter corresponding to the meta-stable state reaches zero by increasing both density and temperature. In other words, by increasing the density and the temperature, the spin polarized SQM becomes nearly unpolarized. We calculated the equation of state of the spin polarized SQM at different temperatures for $B = 5 \times 10^{18} \text{ G}$. It was shown that by increasing temperature, the equation of state of spin polarized SQM becomes stiffer. Finally, using the general relativistic TOV equation, we studied the structure of the spin polarized strange quark star (SQS). The maximum mass and the corresponding radius of spin polarized SQS at different temperatures and magnetic fields were calculated. We have shown that the gravitational mass of spin polarized SQS rapidly increases by increasing the central energy density. We also observed that the mass and the radius of the spin polarized SQS decreases by increasing both temperature and magnetic field.

Acknowledgments

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