Properties of color-flavor locked strange quark matter in an external strong magnetic field (Postprint)

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Full Text

Preamble

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Properties of Color-Flavor Locked Strange Quark Matter in an External Strong Magnetic Field

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Abstract. The properties of color-flavor locked strange quark matter in an external strong magnetic field are investigated in a quark model with density-dependent quark masses. Parameters are determined by stability arguments. It is found that the minimum energy per baryon of the magnetized color-flavor locked (MCFL) matter decreases with increasing magnetic-field strength in a certain range, which makes MCFL matter more stable than other phases within a proper magnitude of the external magnetic field. However, if the energy of the field itself is added, the total energy per baryon will increase.

Keywords: Strange quark matter, MCFL, Mass-density-dependent model
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Introduction

Strange quark matter (SQM) is an interesting topic not only because of its great theoretical significance, but also due to its many applications, such as in studying quantum chromodynamics (QCD) phase diagrams, properties of strangelets, and the structure of compact stars. In 1984, Witten conjectured that quark matter with strangeness might be the true ground state of QCD. Soon after Witten's conjecture, Farhi and Jaffe studied the stability of SQM with the conventional MIT bag model and found that SQM is absolutely stable around normal nuclear density for a wide range of model parameters. Since then, SQM has become a main topic in numerous meaningful works.

It has been demonstrated that SQM at high density may be in the color-flavor locked (CFL) phase where quarks with different color and flavor quantum numbers form Cooper pairs with a large binding energy. It is thus possible that CFL matter, rather than nuclear matter, may be the ground state of strange quark matter at high density. Therefore, a compact star is suggested to include color superconducting quark matter in its inner core.

It is generally believed that properties of quark matter are strongly affected in the presence of a strong magnetic field. Such fields widely exist on the surfaces of stars. The observed magnetic field strength on the surface of pulsars could be on the order of $10^{\{12\}-10}\{13\}$ G, while the magnetic-field strength on so-called magnetars could be on the order of $10^{\{14\}-10}\{15\}$ G or even higher. In fact, the largest magnetic field that can be sustained by strange stars was estimated to be as large as $1.5 \times 10\hat{}\{20\}$ G. Although the origin of strong magnetic fields is not completely clear and remains under active investigation, some mechanisms have been proposed to understand their existence, such as the amplification of a relatively small magnetic field during the star's collapse with magnetic flux conservation, and the magneto-hydrodynamic dynamo mechanism where large magnetic fields are generated by rotating the plasma of a protoneutron star. Furthermore, noncentral high-energy heavy-ion collisions could generate intense magnetic fields as high as about $10\hat{}\{19\}$ G, corresponding to eB_m 6m_π^2 where e is the fundamental electric charge and m_π is the pion mass. It is therefore necessary to study the properties of CFL matter in the presence of an external magnetic field.

In past years, magnetized strange quark matter (MSQM) and CFL matter have been studied with many phenomenological models, such as the bag model, the Nambu-Jona-Lasinio (NJL) model, and the mass-density-dependent model. MCFL matter has a wide range of model parameters characterized by the so-called stability window, and has also been studied in the NJL model as well as in the quasiparticle model.

As is well known, particle masses vary with environment—that is, they depend on density or chemical potential. The equiv-particle model takes this effect into account through density-dependent quark masses. In recent years, this model has been extensively applied to study the properties of SQM. In this paper, we extend it to investigate the properties of CFL matter when a strong magnetic field is present. It is found that MCFL matter is more stable than other phases within a proper magnitude of the external magnetic field. At a fixed density, the energy density of MCFL matter varies with the magnetic field strength. At B_m ≥ 10^{19} G, the energy per baryon, pressure, and quark chemical potentials become smaller because the quantum number of the corresponding Fermi momentum approaches zero.

This paper is organized as follows. In Section II, we present the thermodynamic formulas used for the study of MCFL matter in the equiv-particle model with density-dependent quark masses. We then present the numerical results and discussions in Section III. Section IV provides a short summary.

II. Thermodynamic Treatment

Our starting point is the thermodynamic potential density of a free-particle system:

$$\Omega_0 = \sum_i \frac{g_i}{(2\pi)^3} \int d^{3p} \left(\sqrt{p^2 + m_i^2} - \mu_i \right)$$

where the summation index i runs over u, d, s quarks and electrons, m_i is the corresponding particle mass, _i is the chemical potential, g_i is the degeneracy factor with a value of 3 for quarks and 1 for electrons, while the degeneracy due to spin is accounted for by a factor of 2.

In the case of the CFL phase, due to the energy gap Δ determined by solving the gap equation, a new term should be added to the above expression. The thermodynamic potential density of CFL matter is then

$$\Omega_{\mathrm{CFL}} = \sum_i \frac{g_i}{(2\pi)^3} \int d^{3p} (\epsilon_i - \mu_i) - \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} + B$$

where _i = √(p^2 + m_i^2) is the dispersion relation of a free particle with mass m_i, $\bar{\mu}$ = (_u + _d + _s)/3 is the average of the quark chemical potentials. The second term arises from the pairing contribution, and the last term B is the famous MIT bag constant that accounts for vacuum energy.

To consider the effect of a magnetic field, we assume a constant magnetic field with strength B_m along the z-axis. Due to Landau diamagnetism, the single-particle energy spectrum can be written as

$$\epsilon_{i,l} = \sqrt{p_z^2 + m_i^2 + 2|q_i|B_m[l + 1/2 - \mathrm{sgn}(q_i)S]}$$

where p_z is the component of particle momentum along the magnetic field direction, q_i is the electric charge of quarks (q_u = 2/3, q_d = q_s = -1/3, q_e = -1), l = 0, 1, 2, … is the principal quantum number for allowed Landau levels, and S = $±$1/2 refers to spin-up and spin-down states, respectively. The sign function 'sgn' equals 1 for a positive argument and -1 for a negative argument.

For convenience, one normally sets   = l + 1/2 - sgn(q_i)S, where   = 0, 1, 2, … . The single-particle energy becomes

$$\epsilon_{i,\nu} \equiv \sqrt{p_z^2 + m_i^2 + 2\nu|q_i|B_m}$$

The integration over the p_x–p_y plane in momentum space should be replaced by

$$\int_{-\infty}^{\infty}\int_{-\infty}^{\infty} dp_x dp_y \to 2\pi|q_i|B_m \sum_\nu (2 - \delta_{\nu 0})$$

After this substitution, the thermodynamic potential density in the conventional bag model becomes

$$\Omega_{\mathrm{MCFL}} = -\sum_i \frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\mu_i\sqrt{\mu_i^2 - M_{i,\nu}^2} - M_{i,\nu}^2 \ln\left(\frac{\mu_i + \sqrt{\mu_i^2 - M_{i,\nu}^2}}{M_{i,\nu}}\right)\right] - \frac{3\Delta^2\bar{\mu}^2}{\pi^2} + B$$

where M_{i, }   √(m_i^2 + 2 |q_i|B_m). The upper bound _{max} of the summation index   is

$$\nu_{\max} \equiv \mathrm{int}\left(\frac{\mu_i^2 - m_i^2}{2|q_i|B_m}\right)$$

where the function int(x) means taking the integer part of its argument x.

To include medium effects, the quark masses should be density/chemical-potential-dependent. In the chemical-potential-dependent case, one can use the quasiparticle model, as has been done in Ref. [45]. In the density-dependent case, the actual chemical potential _i should be replaced with an effective chemical potential _i^*:

$$\Omega_0 = \sum_i \frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\mu_i^* \sqrt{\mu_i^{*2} - M_{i,\nu}^2} - M_{i,\nu}^2 \ln \left(\frac{\mu_i^* + \sqrt{\mu_i^{*2} - M_{i,\nu}^2}}{M_{i,\nu}} \right) \right] - \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} + B$$

where $\bar{\mu}$ is now understood as the average of the effective chemical potentials, and Ω_i is connected to the effective chemical potentials by

$$\Omega_i = -\frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\mu_i^* \sqrt{\mu_i^{*2} - M_{i,\nu}^2} - M_{i,\nu}^2 \ln \left(\frac{\mu_i^* + \sqrt{\mu_i^{*2} - M_{i,\nu}^2}}{M_{i,\nu}} \right) \right]$$

All other thermodynamic quantities can be derived from Ω_0. Specifically, the particle number density is given by n_i = - Ω_0/ _i^*, yielding

$$n_i = \frac{g_i|q_i|B_m}{2\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \sqrt{\mu_i^{*2} - M_{i,\nu}^2}$$

The energy density for MCFL matter is then

$$E_{\mathrm{MCFL}} = \Omega_0 + \sum_i \mu_i^* n_i$$

Upon application of the previous equations, we have

$$\Omega_{\mathrm{MCFL}} = -\sum_i \frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\mu_i^* \sqrt{\mu_i^{*2} - M_{i,\nu}^2} - M_{i,\nu}^2 \ln \left(\frac{\mu_i^* + \sqrt{\mu_i^{*2} - M_{i,\nu}^2}}{M_{i,\nu}} \right) \right] - \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} + B$$

$$E_{\mathrm{MCFL}} = \sum_i \frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\mu_i^* \sqrt{\mu_i^{*2} - M_{i,\nu}^2} + M_{i,\nu}^2 \ln \left(\frac{\mu_i^* + \sqrt{\mu_i^{*2} - M_{i,\nu}^2}}{M_{i,\nu}} \right) \right] + \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} + B$$

Because the quark masses are density dependent, the actual chemical potential is generally not equal to its effective counterpart. In fact, they are linked by

$$\mu_i = \mu_i^* + \mu_I$$

where _I arises from the density dependence of the quark masses. Its explicit expression is obtained by applying the fundamental differential equality dE_{MCFL} = Σ_i _i dn_i, giving

$$\mu_I = \sum_j \frac{g_j|q_j|B_m D}{18\pi^2 n^{4/3}} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) m_j \ln\left(\frac{\mu_j^* + \sqrt{\mu_j^{*2} - M_{j,\nu}^2}}{M_{j,\nu}}\right)$$

In the equiv-particle model, the quark mass can be divided into two parts:

$$m_i = m_{i0} + m_I$$

where m_{i0} is the quark's current mass, and m_I represents the effect due to interactions between quarks. In principle, the density dependence of m_I should be determined from QCD. However, as mentioned before, there is presently no way to exactly solve QCD. Therefore, the density dependence is normally given phenomenologically. It can be shown that the following parametrization is reasonable:

$$m_I = \frac{D}{n^{1/3}}$$

where D is a fixed constant determined by stability arguments, n is the total baryon number density, and the exponent of the baryon number density was derived based on in-medium chiral condensates and linear confinement at zero temperature. This form satisfies lim_{n$→$0} m_I = ∞ and lim_{n→∞} m_I = 0, which are the requirements of quark confinement and asymptotic freedom.

Because weak equilibrium is always reached in SQM, the relevant chemical potentials satisfy

$$\mu_d = \mu_s, \quad \mu_u + \mu_e = \mu_s$$

Therefore, the effective chemical potentials also satisfy the corresponding relations:

$$\mu_u^* + \mu_e = \mu_d^* = \mu_s^*$$

Due to the external magnetic field, the longitudinal pressure and transverse pressure become different:

$$P_{\parallel} = -\Omega_0 + \sum_i \mu_i n_i - M_f B_m$$

$$P_{\perp} = -\Omega_0 + \sum_i \mu_i^* n_i$$

where P_ is the total parallel pressure and P_ is the transverse pressure. The system magnetization is given by

$$M_f = -\sum_i \sum_\nu \frac{\partial \Omega_i}{\partial M_{i,\nu}} \frac{dM_{i,\nu}}{dB_m}$$

Upon application of the relevant equations, we have the following explicit expressions:

$$P_{\parallel} = -\sum_i \frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\sqrt{\mu_i^{*2} - M_{i,\nu}^2} + \frac{M_{i,\nu}^2}{\mu_i^*} \ln\left(\frac{\mu_i^* + \sqrt{\mu_i^{*2} - M_{i,\nu}^2}}{M_{i,\nu}} \right) \right] - \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} - B$$

$$P_{\perp} = -\sum_i \frac{g_i|q_i|B_m}{4\pi^2} \sum_{\nu=0}^{\nu_{\max}} (2-\delta_{\nu 0}) \left[\sqrt{\mu_i^{*2} - M_{i,\nu}^2} + \frac{m_i + 2|q_i|\nu B_m}{\mu_i^*} \ln\left(\frac{\mu_i^* + \sqrt{\mu_i^{*2} - M_{i,\nu}^2}}{M_{i,\nu}} \right) \right] - \frac{3\Delta^2 \bar{\mu}^2}{\pi^2} - B$$

We also have the baryon number density n = (n_u + n_d + n_s)/3 and the charge density Q = (2/3 n_u - 1/3 n_d - 1/3 n_s - n_e). The charge-neutrality condition requires Q = 0.

For a given total baryon number density n, we can obtain the respective _u^, _d^, _s^*, and _e by solving the relevant equations with the help of the number density formula. The number densities n_u, n_d, n_s, and n_e can then be obtained. The energy density is calculated using the energy density equation, while the pressures are obtained from the pressure equations for different values of B, D, and B_m.

III. The Properties of MCFL Matter

[Figure 1: see original paper] shows the energy per baryon of SQM, MSQM, CFL matter, and MCFL matter, respectively, as a function of baryon number density. Because the current masses of u/d quarks are very small, we simply take m_{u0} = m_{d0} = 0. For the current mass of the strange quark, we take m_{s0} = 80 MeV. The electron does not participate in the strong interaction, its mass is very tiny, and is also ignored. For convenience of comparison with previous works, we take the pairing parameter to be Δ = 100 MeV. The bag constant B and the confinement parameter D are taken to be $B^{1/4} = 140$ MeV and $D^{1/2} = 120$ MeV.

In our calculation, we assume the magnetic field to be constant with its direction along the z-axis. Because the system becomes unstable when the magnetic field strength is higher than 10^{20} G, as discussed by Chakrabarty, we take the magnetic field strength to be $B_m = 10^{19}$ G. Three features are evident from top to bottom in Fig. 1. Firstly, the energy minimum (solid triangle) corresponds exactly to zero pressure (open circle) for each case. In fact, the exact coincidence of the lowest energy state and zero pressure is a basic requirement of fundamental thermodynamics, as pointed out in Ref. [15] and derived in detail in Ref. [1]. Secondly, the energy per baryon of CFL matter and MCFL matter is lower than that of SQM and MSQM, showing that the quark pairing effect greatly increases the stability of SQM. Thirdly, the energy per baryon of MSQM and MCFL matter is lower than that of SQM and CFL matter, respectively, demonstrating that an external magnetic field of proper magnitude lowers the energy per baryon through the rearrangement of Landau energy levels in magnetized quark matter. Generally, we have the inequality relation for the energy per baryon:

$$E_{\mathrm{MCFL}} < E_{\mathrm{CFL}} < E_{\mathrm{MSQM}} < E_{\mathrm{SQM}}$$

[Figure 2: see original paper] shows the minimum energy per baryon of MCFL matter as a function of magnetic field strength. When the magnetic field strength B_m is small, the energy is nearly constant. The energy per baryon starts to decrease noticeably as a function of the magnetic field between 10^{18} G and 10^{19} G. When the magnetic field strength exceeds 10^{19} G, the energy per baryon decreases quickly. Therefore, an external magnetic field with proper strength lowers the energy per baryon. In this regard, one should note that the energy from the external magnetic field was not added; otherwise, the total energy per baryon would increase.

There are different views on whether the energy contribution from the magnetic field should be included. If one would like to include the field contribution, one should know how the quark matter produces the magnetic field. As mentioned in the introduction, the origin of strong magnetic fields is presently not very clear, although some mechanisms have been proposed. Therefore, we treat the magnetic field as an externally applied field.

[Figure 3: see original paper] shows the pressure in MCFL matter as a function of magnetic field strength at two (solid line) and three (short-dot line) times the nuclear saturation density $n_0 = 0.165$ fm^{-3}. As is well known, space becomes anisotropic when an external magnetic field is present. To compare the magnitude of longitudinal and transverse pressures, we plot P_ and P_ at given densities of $n = 2n_0$ (solid line) and $n = 3n_0$ (short-dot line) as functions of magnetic field strength. The difference between P_ and P_ reflects the breaking of rotational symmetry by the magnetic field. The pressure remains constant when the magnetic field strength is lower than 10^{18} G. When the magnetic field strength exceeds 10^{18} G, the pressure anisotropy becomes noticeable: the parallel pressure P__ increases far beyond the constant value, while the transverse pressure P__ decreases from the constant value.

[Figure 4: see original paper] shows the chemical potentials of quarks in MCFL matter as a function of magnetic field strength for $n = 3n_0$. When the magnetic field strength B_m is small, all chemical potentials _u, _d, _s, and _e are approximately constant. The chemical potentials oscillate when the magnetic field strength is in the range of 10^{18} G to 10^{19} G. When the magnetic field strength exceeds a critical value of about 10^{19} G, the energy decreases rapidly. In the range $B_m \geq 10^{19}$ G, the chemical potentials decrease with the magnetic field. This is also why the pressure oscillates and decreases with increasing magnetic field.

IV. Conclusion

We have extended the equiv-particle model with density-dependent quark masses to investigate MCFL matter in an external strong magnetic field. The exact zero pressure at the energy minimum demonstrates the self-consistency of our treatment. The stability properties of MCFL matter are calculated and compared with SQM, MSQM, and CFL matter. For a proper magnitude of the external magnetic field, the MCFL phase is more stable than other phases of quark matter. The impact of the external strong magnetic field on the properties of MCFL matter depends on the magnetic-field strength. When $B_m \leq 10^{18}$ G, the magnetic field affects the system properties only slightly. When 10^{18} G $\leq B_m \leq 10^{19}$ G, Landau oscillations appear in the chemical potentials, and the effect becomes obvious. When $B_m \geq 10^{19}$ G, the maximum Landau level _{max} takes only the lowest value, and accordingly, the effects on the chemical potential, energy density, and pressure are all dramatically large. Importantly, in this case the minimum energy per baryon becomes smaller.

Naturally, the present study is limited in many aspects while the quark matter field is rapidly developing. Therefore, further investigations are needed.

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Note: Figure translations are in progress. See original paper for figures.