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Quark matter and quark stars in strong magnetic fields at finite temperature within the confined-isospin-density-dependent mass model

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ABSTRACT

We study the properties of strange quark matter (SQM) and quark stars (QSs) in strong magnetic fields within the extended confined isospin-density-dependent mass (CIDDM) model including the temperature dependence of the equivalent mass for quarks. The quark symmetry energy, quark symmetry free energy, and the equation of state (EOS) of SQM in constant magnetic fields at finite temperature are investigated, and it is found that including the temperature dependence in CIDDM model and considering strong magnetic fields can both significantly influence the properties of the SQM and the maximum mass of quark stars. Using the density-dependent magnetic field and assuming two extreme cases for the magnetic field orientation in QSs (the radial orientation in which the local magnetic fields are along the radial direction and the transverse orientation in which the local magnetic fields are randomly oriented but perpendicular to the radial orientation), we analyze the mass-radius relations for different stages of the protoquark stars (PQSs) along the star evolution. Our results indicate that the maximum mass of magnetized PQSs may depend on not only the strength distribution and the orientation of the magnetic fields inside the PQSs, but also the heating process and the cooling process in the star evolution.

1. Introduction

The investigation of the properties of strong interaction matter is one of the fundamental issues in nuclear physics and astrophysics. In terrestrial laboratories, the experiments of high energy heavy ion collisions (HICs) can provide the unique tool to explore the properties of strong interaction matter. The hot and dense quark matter might be created in HICs from the Nuclotron-based Ion Collider Facility (NICA) at JINR and the Facility for Antiproton and Ion Research (FAIR) at GSI, while the hot quark-gluon plasma (QGP) is expected to be created in HICs at the Large Hadron Collider (LHC) at CERN and the Relativistic Heavy Ion Collider (RHIC) at BNL. In nature, neutron stars (NSs) provide a unique astrophysical testing grounds of our knowledge to explore the properties of strong interaction matter, especially the equation of state (EOS) of neutron-rich matter, at low temperature and high baryon density [1,2].

Theoretically, NSs may be converted to strange quark stars (QSs), which are made of deconfined absolutely stable u, d and s quark matter in β-equilibrium condition, i.e., strange quark matter (SQM). The possible existence of QSs is one of the most intriguing aspects of modern astrophysics and cannot be conclusively ruled out [3–9]. In QSs, there exists large $u-d$ quark asymmetry (isospin asymmetry) in the star matter, which indicates the importance of the isovector properties in SQM, and the numbers of u and d ($\bar{u}$ and $\bar{d}$) quarks can be generally found unequal in high energy HICs at RHIC/LHC, which is also isospin asymmetric. Therefore it is of great interests and critical importance to study the isovector properties of quark star matter (one can describe these properties by studying the quark matter symmetry energy and quark matter symmetry free energy), the isospin-dependence of the QCD phase diagram, and the isospin effects of partonic dynamics in high energy HICs.

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When massive stars exhaust the fuel supply, the type II supernova explosion is triggered, which will cause the core to be crushed by gravity and may form a newly-born compact star (protoneutron star (PNS) or protoquark star (PQS)) [10–13] or a black hole. At the beginning stage of the birth of a PQS, the lepton number per baryon with the trapped neutrinos is approximately 0.4 and the entropy per baryon is about one [13]. During the following 10–20 seconds, the star matter will be heated by the diffusing neutrinos, and the entropy per baryon will increase to two, while the neutrino fraction is almost zero. Then the PQSs begins cooling down at the third stage and finally forms into the cold QSs [14–16].

In recent decades, the properties of SQM at finite temperature under strong magnetic fields have attracted lots of interests, and the presence of external magnetic field may harden the EOS of SQM when considering that the NSs can be endowed with strong magnetic fields [17], i.e., magnetars. At the surface of the compact star, the magnetic field strength is estimated as $B \sim 10^{14}$ G [18–20], and the magnetic field strength may reach as large as $B \sim 10^{20}$ G in the core of the self-bound QSs [21,22]. Under such strong magnetic fields, the spatial rotational symmetry will break and one should introduce the pressure anisotropy of this system [22–25]. In [26], the authors use a density-dependent magnetic field profile [27,28] and investigate the properties of magnetars by assuming two extreme cases for the orientation inside the quark stars (one is that the local magnetic fields are along the radial direction in QSs, which is denoted as "radial orientation", while the other one is that the magnetic fields are perpendicular to the radial direction but randomly oriented in the plane perpendicular to the radial direction, which is denoted as "transverse orientation") at zero temperature.

In the present work, we extend the confined isospin-density-dependent mass (CIDDM) model to include temperature dependence of the equilibrium mass of quarks to investigate the quark matter symmetry free energy/ symmetry free energy and the equation of state (EOS) for SQM in constant magnetic fields at finite temperature. The properties of PQSs under strong magnetic fields are also studied, and we find that the maximum mass of magnetized PQSs may depend on not only the strength distribution and the orientation of the magnetic fields inside the stars, but also the heating and cooling process in the star evolution.

2. Models and methods

2.1. The confined isospin-density-dependent mass model

The CIDDM model [26,29,30] extends the confined density-dependent mass model (i.e., the CDDM) model [31–39] by including the isospin dependence for the equivalent quark mass. With baryon number density n_B and isospin asymmetry δ, the quark mass can be expressed as

$$\begin{aligned} m_q &= m_{q_0} + m_I + m_{iso} \\ &= m_{q_0} + \frac{D}{{n_B}^z} - \tau_q \delta D_I n_B^{\alpha} e^{-\beta n_B}, \end{aligned} \tag{1}$$

where m_{q0} is the quark current mass, $m_I = \frac{D}{{n_B}^z}$ represents the flavor-independent quark interactions, while $m_{iso} = -\tau_q \delta D_I n_B^{\alpha} e^{-\beta n_B}$ is the isospin dependent part. For $m_I = \frac{D}{{n_B}^z}$, z is the equivalent mass scaling parameter and D can be determined by the stability arguments of SQM. For $m_{iso} = -\tau_q \delta D_I n_B^{\alpha} e^{-\beta n_B}$, the parameters D_I, α and β can determine the isospin-density dependence of the effective interactions in quark matter, τ_q means the isospin quantum number of quarks, and we set $\tau_q = 1$ for $q = u$ (u quarks), $\tau_q = -1$ for $q = d$ (d quarks), and $\tau_q = 0$ for $q = s$ (s quarks). The isospin asymmetry is defined from the works [29,40–43] as

$$\delta = 3\frac{n_d - n_u}{n_d + n_u}. \tag{2}$$

In Eq. (1), the quark confinement condition $\lim_{n_B \to 0} m_q = \infty$ will be guaranteed if the scaling parameter $z > 0$ and $\alpha \geq 0$. In addition, if $\beta > 0$, then $\lim_{n_B \to \infty} m_{iso} = 0$, which satisfies the asymptotic freedom $\lim_{n_B \to \infty} m_q = m_{q0}$. The readers are referred to Ref. [29] for more details about the CIDDM model.

Using the similar way as in Ref. [44] and Ref. [45], we introduce the temperature dependence of equivalent mass for quarks in the CIDDM model by considering the linear confinement and string tension $\sigma(T)$, and the equivalent quark mass is modified as

$$m_q = m_{q_0} + \left(\frac{D}{{n_B}^z} - \tau_q \delta D_I n_B^{\alpha} e^{-\beta n_B} \right) \sigma(T), \tag{3}$$

with

$$\sigma(T) = 1 - \frac{8T}{\lambda T_c} \exp\left(-\lambda \frac{T_c}{T}\right), \tag{4}$$

where $q = u, d, s$, $\sigma(T)$ is the temperature dependent string tension [46], $T_c = 170$ MeV is the critical temperature calculated from LQCD [47], and $\lambda = 1.605812$ is determined as the solution of the equation $1 - \frac{8T}{\lambda T_c} \exp(-\lambda \frac{T_c}{T}) = 0$ when $T = T_c$. One can find that m_q decreases as temperature increases, and the equivalent mass will reach the quark current mass m_{q0} when temperature hits the critical value T_c, which shows the chiral symmetry restoration feature.

2.2. Properties of SQM

The weak beta-equilibrium condition for SQM (we assume it is composed of u, d, and s quarks and e, μ, ν_e and ν_μ leptons with electric charge neutrality in beta-equilibrium) can be expressed as

$$\mu_d = \mu_s = \mu_u + \mu_e - \mu_{\nu_e}, \tag{5}$$

$$\mu_\mu = \mu_e \quad \text{and} \quad \mu_{\nu_\mu} = \mu_{\nu_e}. \tag{6}$$

And the electric charge neutrality condition can be written as

$$\frac{2}{3}n_u = \frac{1}{3}n_d + \frac{1}{3}n_s + n_e + n_\mu. \tag{7}$$

In an external constant magnetic field with strength B, the energy spectrum for quarks and leptons with electric charge q_i can be expressed as [48]

$$E_{p,i} = \sqrt{p_z^2 + 2\nu|q_i|B + m_i^2}, \tag{8}$$

where m_i is the quark mass, p_z is the momentum in the z direction (the magnetic field is assumed to be along the z axis), $\nu = n + \frac{1}{2} - \frac{q_i}{|q_i|}\frac{s}{2}$ is the Landau levels with $n = 0, 1, 2, 3, \ldots$ being the principal quantum number, and $s = +1$ for spin-up while $s = -1$ for spin-down. In this paper, we do not consider the contributions from the anomalous magnetic moments because the anomalous magnetic moments are not well understood in for quark matter in the deconfined condition and are not important for leptons [25,27,28,49–52].

The total thermodynamic potential density for SQM at finite temperature under strong magnetic fields can be written as

$$\Omega = \sum_i \Omega_i, \tag{9}$$