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Quark star matter at finite temperature

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We have investigated the properties of strange quark matter and quark stars at finite temperature within the confined isospin-density-dependent mass (CIDDM) model. The newly discovered heavy compact stars PSR J0348 + 0432 ($2.01 \pm 0.04\ M_\odot$) and MSP J0740 + 6620 ($2.14 \pm^{0.10}_{0.09}\ M_\odot$ of 68.3% credibility interval and $2.14 \pm^{0.20}_{0.18}\ M_\odot$ of 95.4% credibility interval) can be well described as quark stars with large quark matter symmetry energy within the CIDDM model in this work. In particular, we also calculate the properties of the protoquark stars (PQSs) at the heating and cooling stages along the star evolution line, and we find that the tidal deformability of PQSs increases with temperature in the heating stages within the CIDDM model.

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I. INTRODUCTION

Recently, the direct detection of the gravitational wave (GW) signal GW170817 has been reported by the LIGO-Virgo collaboration from a binary compact star system [1]. In Refs. [2–11], many constraints on the equation of state (EOS) of the strongly interacting matter and the maximum mass of the compact stars have been performed by considering the results from the observation. Since the tidal deformability can also constrain the properties of the EOS for star matter, the LIGO-Virgo collaboration sets the upper limit on the tidal deformability of the 1.4 solar mass compact stars as $\Lambda_{1.4} < 800$ for the low-spin priors [1]. Then the new limitations on the properties of the nuclear matter symmetry energy and EOSs of strongly interacting matter have been calculated in Refs. [5,8,9,12–15]. In Ref. [16], the new constraints for the tidal deformability parameter $\tilde{\Lambda}$ have been updated as (0,630) for large component spins, 300^{+420}_{-230} by using the highest posterior density interval, and $\Lambda_{1.4} = 190^{+390}_{-120}$ by estimating through a linear expansion of Λm^5 around 1.4 solar mass [5,17]. In the works [4,18,19], the GW observation of tidal deformability can also constrain the properties of the EOS for hybrid stars (HS) and quark stars, and the results show that GW170817 has the possibility of originating from a binary quark star merger or a binary hybrid star merger.

Compact stars, in nature, provide an ideal astrophysical testing ground to explore the properties of the strongly interacting matter at high baryon density [20–23]. Theoretically, quark stars (QSs) [24–26], which are composed of strange quark matter (SQM), are suggested as another possible candidate of compact stars and cannot be conclusively ruled out [27–34]. The important features for quark stars is that QSs usually have smaller radii than neutron stars (NSs) at a fixed star mass, and the EOS of SQM for QSs will be softened due to the s quark addition. In recent observation, massive compact star PSR J1614-2230 was precisely measured to be $1.97 \pm 0.04\ M_\odot$ [35], which seems to rule out most conventional QS models. In 2010, a heavy pulsar PSR J0348 + 0432 with the mass of $2.01 \pm 0.04\ M_\odot$ was discovered by [36], which sets a new record for the star mass. In Ref. [37], the mass of the pulsar MSR J0740 + 6620 ($2.14 \pm^{0.10}_{0.09}\ M_\odot$ of 68.3% credibility interval and $2.14 \pm^{0.20}_{0.18}\ M_\odot$ of 95.4% credibility interval) is measured by combining the relativistic Shapiro delay data at the North American Nanohertz Observatory for Gravitational Waves with the recent orbital-phase-specific observations using the Green Bank Telescope, which is highly likely to be the most massive observed pulsar and provides new constraints on the symmetry energy and EOS for strongly interacting matter.

In consideration of large *u*-*d* quark asymmetry (i.e., isospin asymmetry) appearing in the quark matter formed

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in high energy HICs and quark stars, the isovector properties of SQM may play an important role in determining the properties of proto-quark stars (PQSs) and protohybrid stars [38–43] along the star evolution line. In order to investigate the isospin properties of the star matter and maximum mass of quark star at finite temperature, several works were done to explore the properties of PQS [44–52]. Since the temperature of the hypermassive or supermassive remnant increases during the star merger evolution and there exist few works on the properties of the tidal deformability at finite temperature, temperature dependent EOSs are needed for PQSs or within a binary QSs merger scenario (we should mention that the GW constraints from GW170817 are detected during the late inspiral phases of the star merger at zero temperature case, which are not suitable to constrain the properties of compact stars at finite temperature case in this work) [53–56]. It is of great interest and importance to investigate the isospin effects and the thermodynamical properties of quark matter and QSs at finite temperature.

In this work, we first choose the confined isospin-density-dependent mass (the CIDDM) model to describe the newly observed massive compact stars as quark stars, and then investigate the isospin properties of the quark matter and quark stars at finite temperature. In the end, we calculate the tidal deformability of QSs at zero and finite temperature cases in order to reveal the correlation between the isospin effects and the tidal deformability of QSs.

II. MODELS AND METHODS

A. The confined isospin- and density-dependent mass model

In works [57,58], we extend the confined density-dependent mass (CDDM) model [59–66] to the confined isospin-density-dependent mass (the CIDDM) model by including the isospin dependence of the equivalent mass for quarks. The equivalent mass at zero temperature is expressed as

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

where m_{q0} is the quark current mass, n_B stands for the baryon density, τ_q is the isospin quantum number of quarks, z is the mass scaling parameter, D is the parameter adjusted by stability arguments of SQM, and the constants D_I, α, and β are parameters determining the isospin-density dependence in quark matter. The isospin asymmetry is defined as [57,67–70]

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

In the work [71], the authors extend the CIDDM model by considering the linear confinement and string tension $\sigma(T)$ [72,73], and the temperature dependent equivalent mass is written as

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

where $q = u, d, s$, $\sigma(T) = 1 - \frac{8T}{\lambda T_c}\exp\left(-\lambda\frac{T_c}{T}\right)$ is the temperature dependent string tension [74], $T_c = 170$ MeV is the critical temperature [75], and $\lambda = 1.60581199632$ is determined by imposing $\sigma(T_c) = 0$

B. Properties of quark matter

Similar to the case of nuclear matter [76], the quark matter symmetry energy can be expressed as [57,58,71,77–80],

$$E_{\mathrm{sym}}(n_B, n_s) = \frac{1}{2!}\frac{\partial^2 E(n_B, \delta, n_s)}{\partial \delta^2}\bigg|_{\delta=0}, \tag{4}$$

where E is the energy per baryon of quark matter, and the total energy density for quark matter can be written as

$$E = -\sum_i \frac{g_i}{2\pi^2}\int_0^\infty \left[\frac{\epsilon_i}{1 + e^{(\epsilon_i - \mu_i^*)/T}} + \frac{\epsilon_i}{1 + e^{(\epsilon_i + \mu_i^*)/T}}\right] p^2 \mathrm{d}p - T\frac{\partial \Omega_i}{\partial m_i}\frac{\partial m_i}{\partial T}. \tag{5}$$

Here $\epsilon_i = \sqrt{m_i^2 + p^2}$, μ_i^* is the effective chemical potential, and the degeneracy factor g_i is 6 for quarks ($g_i = 2$ for leptons).

For the $\mathrm{i_{th}}$ particle, the particle density can be written as

$$n_i = \frac{g_i}{2\pi^2}\int_0^\infty \left[\frac{1}{1 + e^{(\epsilon_i - \mu_i^*)/T}} - \frac{1}{1 + e^{(\epsilon_i + \mu_i^*)/T}}\right] p^2 \mathrm{d}p. \tag{6}$$

The quark star matter is conventionally considered as strange quark matter (SQM), which is composed of u, d, and s and leptons with electric charge neutrality in beta-equilibrium. The weak beta-equilibrium condition and the electric charge neutrality condition for SQM can be expressed as

$$\mu_d = \mu_s = \mu_u + \mu_e - \mu_{\nu_e}, \tag{7}$$

and

$$\frac{2}{3}n_u = \frac{1}{3}n_d + \frac{1}{3}n_s + n_e + n_\mu. \tag{8}$$

For more details about the CIDDM model, the readers are referred to Ref. [57].

III. RESULTS AND DISCUSSIONS

Following the Ref. [57], the set of parameters for the current mass of particles we used is $m_{u0} = m_{d0} = 5.5$ MeV, $m_{s0} = 80$ MeV, $m_e = 0.511$ MeV, and $m_\mu = 105.7$ MeV. We use two typical sets of parameters: (1) DI-85 with $D_I = 85$, $D = 22.922$ MeV fm^{3z}, $\alpha = 0.7$, $\beta = 0.1$ fm^3, and $z = 1.8$, and (2) DI-245 with $D_I = 245$, $D = 17.797$ MeV fm^{3z}, $\alpha = 0.7$, $\beta = 0.1$ fm^3, and $z = 1.8$, where the former parameter set can be used to describe the large-mass pulsar PSR J0348 + 0432 with the mass of 2.01 ± 0.04 $M_\odot$ [36] as a QS at zero temperature within the CIDDM model [57], while the latter parameter set can be used to describe the recently discovered the most massive compact star MSR J0740 + 6620 ($2.14\,{}^{+0.10}_{-0.09}$ $M_\odot$ of 68.3% credibility interval and $2.14\,{}^{+0.20}_{-0.18}$ $M_\odot$ of 95.4% credibility interval) [37] as a QS at zero temperature within the CIDDM model. We set $\alpha = 0.7$ and $\beta = 0.1$ fm^3 to match the density dependence of the symmetry energy of the free quark fermi gas [57]. The values of the parameter D for DI-85 and DI-250 are fixed in order to guarantee the stability of SQM.

A. Quark matter symmetry energy at finite temperature

In [14,57,71], we investigate the thermodynamical properties of asymmetric quark matter within the CIDDM model at zero and finite temperature, which indicates that the symmetry energy and the EOS of SQM are mainly sensitive to the isospin dependence in the equivalent quark mass. The results also show that if the scaling parameter is set as $z = 1.8$, the quark matter symmetry energy at zero temperature should be at least about twice than that of a free quark gas at the baryon density 1.5 fm^{-3} in order to describe PSR J0348 + 0432 as a QS. Since the previous works have shown the significance of the isospin effects on the properties of quark matter and quark stars within different phenomenological models, we first study the quark matter symmetry energy of asymmetric quark matter at finite temperature within the CIDDM model.

Shown in Fig. 1 is the two-flavor *u-d* quark matter symmetry energy as functions of temperature with different D_I in the CIDDM model. The parameter sets we choose are DI-85 and DI-245, which can describe PSR J0348 + 0432 (2.01 ± 0.04 $M_\odot$) and MSR J0740 + 6620 ($2.14\,{}^{+0.10}_{-0.09}$ $M_\odot$ of 68.3% credibility interval and $2.14\,{}^{+0.20}_{-0.18}$ $M_\odot$ of 95.4% credibility interval) as quark stars with the minimum D_I (and thus the smallest symmetry energy of quark matter) at zero temperature. Since the quark matter symmetry energy usually increase with the increment of the baryon density, in order to see the symmetry energy varies more obviously, we fix the baryon density in Fig. 1 at 1 fm^{-3}, which is often calculated as the central density of the maximum mass for quark stars from many quark phenomenological models.

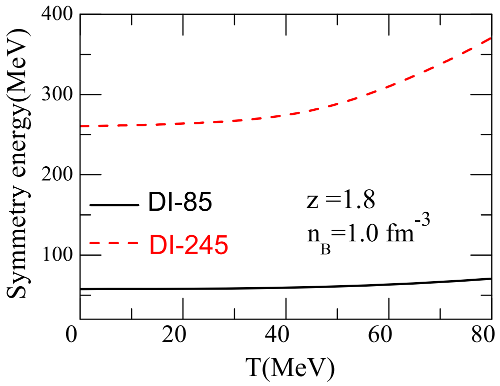

FIG. 1. Two-flavor *u-d* quark matter symmetry energy as functions of temperature within the CIDDM model using different DI, when the baryon density is 1 fm^{-3}.

One can find in Fig. 1 that the quark matter symmetry energy increases with the temperature for both D_I cases. The value of the symmetry energy for $D_I - 85$ increases from 57.5 MeV to 78.9 MeV with temperature increasing from 0 to 80 MeV, while for $D_I - 245$ case, the value of the symmetry energy increases from 260.5 MeV to 370.7 MeV, which indicates a stronger isospin interaction among the quark matter. The result implies that (1) the isospin effects from the quark matter symmetry energy increase with the temperature; (2) the increasing symmetry energy may further stiffen the EOS of SQM; (3) the stiff EOS can support heavier quark stars.

B. Quark stars at finite temperature

In Fig. 2, we demonstrate the maximum mass of QSs as functions of temperature within the CIDDM model by using DI-85 and DI-245. In Ref. [53], the results suggest that the stability of a hypermassive compact star should be caused by the star rotation profile, which is deeply connected with the spatial temperature distribution inside the compact stars. In this work, we mainly focus on the properties of the star matter at high temperature during the merger and postmerger evolution for quark stars, and we consider the temperature inside stars being uniform for ease of calculation. Following the SQM conjecture [27–29,

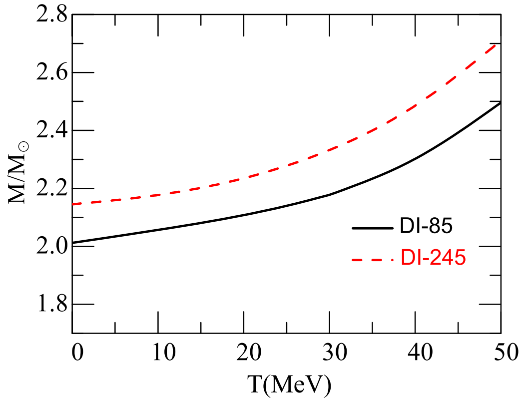

FIG. 2. Maximum mass for quark stars using DI-85 and DI-245 at different temperatures within the CIDDM model.

31,32], the so-called absolute stability condition for SQM requires that the minimum energy per baryon of SQM should be less than the minimum binding energy per baryon of observed nuclei, i.e., $\mathrm{M}(^{56}Fe)c^2/56 = 930$ MeV, while the minimum energy per baryon of the pure two-flavor *u-d* quark matter should be larger than 930 MeV in order to be consistent with the standard nuclear physics. In the present work, the two parameter sets DI-85 and DI-245 can both fulfill the requirements of the absolute stability condition for SQM. One can see from Fig. 2 that the CIDDM model with DI-245 can describe MSR J0740 + 6620 ($2.14\,\pm^{0.10}_{0.09}\ M_\odot$ of 68.3% credibility interval and $2.14\,\pm^{0.20}_{0.18}\ M_\odot$ of 95.4% credibility interval) as a quark star at zero temperature, which is hard for most of the phenomenological quark models to support such massive quark stars. One can also find both the maximum masses of QSs for DI-85 and DI-245 are increasing with the increment of temperature, which indicates that the EOS of SQM becomes stiffer when the isospin effects increase with temperature. Furthermore, one can find that the value and the growth rate of the maximum mass of the QSs for DI-245 are larger than that for DI-85, which is in agreement with the conclusions taken from the results in Fig. 1 that the larger symmetry energy can increase the isospin effects in quark matter and stiffen the EOS of the star matter.

In Fig. 3, we calculate the tidal deformability at 1.4 star mass as functions of the temperature with DI-85 and DI-245 within the CIDDM model. One can find that the tidal deformability increases from 241.6 (T = 0) to 487.3 (T = 50 MeV) for DI-85, while for DI-245 $\Lambda_{1.4}$ increases from 345.9 (T = 0) to 655.7 (T = 50 MeV), which shows that we can describe both PSR J0348 + 0432 and PSR J0740 + 6620 as quark stars at zero temperature by considering the already mentioned constraints in tidal deformability $\Lambda_{1.4} < 800$ and $\Lambda_{1.4} = 190^{+390}_{-120}$. From the results in Fig. 1 and Fig. 2, one can obtain that the quark matter symmetry energy and the quark star mass increase with temperature, which indicates the isospin effects in the EOS of the star matter increase with the increment of the temperature within the CIDDM model. In Fig. 3, it can be found that the tidal deformability of the QSs can also increase with temperature, which implies that the tidal deformability of QSs might depend on the isospin interaction inside the star matter within the CIDDM model ($\Lambda_{1.4}$ increases with the increment of the quark matter symmetry energy).

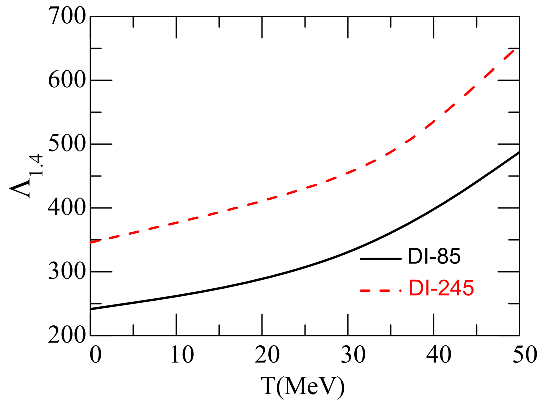

FIG. 3. $\Lambda_{1.4}$ as functions of the temperature with different D_I in the CIDDM model.

C. Protoquark stars

Shown in Fig. 4 is the mass of PQS as functions of the radius at three snapshots along star evolution within the CIDDM model with DI-85 and DI-245, and the shaded band represents the pulsar mass of 2.01 ± 0.04 $M_\odot$ from PSR J0438 + 0432 and the pulsar mass of $2.14\,\pm^{0.20}_{0.18}\ M_\odot$ of 95.4% credibility interval from MSR J0740 + 6620.

The protoquark star usually forms after the supernova explosion. At the birth of the PQS, the number of leptons per baryon with trapped neutrinos is fixed as 0.4 with the entropy per baryon being one [43,50]. In the following tens of seconds, neutrinos all escape and heat the star matter [44], which inspires the star to the maximally heated star with the entropy per baryon being 2. After the heating stage, the star begins cooling down [43,50], and this stage is identical to the zero temperature case for QSs. In Fig. 4, we calculate the maximum mass of the stars at three snapshots along the star evolution line as [48–52]

$$\text{(I)}\ S/n_B = 1, \qquad Y_l = 0.4, \tag{9}$$

$$\text{(II)}\ S/n_B = 2, \qquad Y_{\nu_l} = 0, \tag{10}$$

$$\text{(III)}\ S/n_B = 0, \qquad Y_{\nu_l} = 0. \tag{11}$$

One can find in Fig. 4 that the star mass of the PQSs is larger in the heating stage (stage I and stage II) than the star

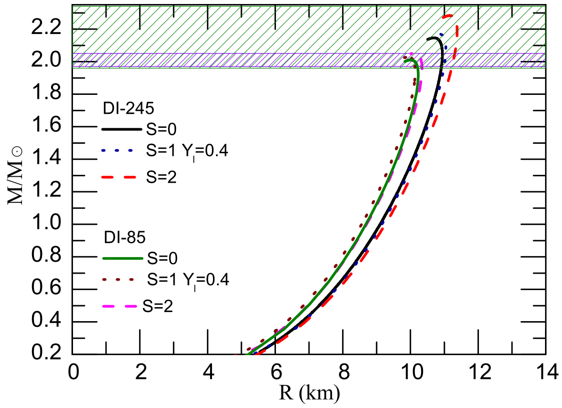

FIG. 4. Maximum mass of PQS as functions of the radius at three snapshots along star evolution within the CIDDM model with DI-85 and DI-245. The shaded band represents the pulsar mass of 2.01 ± 0.04 $M_\odot$ from PSR J0438 + 0432 and the pulsar mass of $2.14\,\pm^{0.20}_{0.18}\ M_\odot$ from PSR J0740 + 6620.

mass in the cooling stage (stage III) with DI-85 and DI-245, and it can be found that the largest star mass case will appear when the evolution reaches the 2nd stage (2.05 $M_\odot$ for DI-85 and 2.28 $M_\odot$ for DI-245). One can also find that the growth rate of the star mass of PQSs along the heating stages for DI-245 is larger than that for DI-85, and this result is consistent with the results in Fig. 2, where the temperature dependence of the star mass at finite temperature for DI-245 is stronger than that for DI-85. In order to investigate the properties of the tidal deformability of the PQSs, we also calculate $\Lambda_{1.4}$ at three stages along star evolution. The results show that the tidal deformability $\Lambda_{1.4}$ are 355.2, 388.7, and 345.9 at the 1st, 2nd, and 3rd stages, respectively for DI-245 case, which indicates that the tidal deformability of the PQSs increases with the heating process within the CIDDM model.

IV. CONCLUSION AND DISCUSSION

In this work, we have calculated the quark matter symmetry energy, the maximum mass of QSs at finite temperature, the tidal deformability for QSs, and the properties of protoquark stars within the CIDDM model. We have found that considering the temperature effects on the star matter can significantly change the isospin effects and thermodynamical properties of the star matter.

We have calculated the maximum mass and the tidal deformability of QSs at finite temperature within the CIDDM model. We have found that both the maximum mass and the tidal deformability increase with the temperature, and we can describe the most massive compact star MSR J0740 + 6620 as quark stars. We have also found that the tidal deformability of QSs increases with the increment of the quark matter symmetry energy, which indicates that $\Lambda_{1.4}$ might depend on the isospin interaction inside the star matter within the CIDDM model.

Furthermore, we have investigated the properties of the PQSs at the heating and cooling stages along the star evolution line. The results show that the tidal deformability of PQSs increases with the heating process within the CIDDM model. In future, more possible discovery of heavy compact stars and accurate bound for $\Lambda_{1.4}$ would put strict constraints on the EOS and the symmetry energy for quark matter.

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