Hyperon effects in covariant density functional theory and recent astrophysical observations

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Motivated by recent observational data, the equations of state with the inclusion of strangeness-bearing Λ hyperons and the corresponding properties of neutron stars are studied based on the covariant density functional (CDF) theory. To this end, we specifically employ the density-dependent relativistic Hartree-Fock (DDRHF) theory and the relativistic mean field (RMF) theory. The inclusion of Λ hyperons in neutron stars shows substantial effects in softening the equation of state. Because of the extra suppression effect originating from the Fock channel, large reductions on both the star mass and radius are predicted by the DDRHF calculations. It is also found that the mass-radius relations of neutron stars with Λ hyperons determined by DDRHF with the PKA1 parameter set are in fairly good agreement with the observational data, where a relatively small neutron-star radius is required. Therefore, it is expected that the exotic degrees of freedom such as the strangeness-bearing structure may appear and play significant roles inside the neutron stars, which is supported further by the systematical investigations on the consistency between the maximum neutron-star mass and Λ-coupling strength.

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I. INTRODUCTION

As the natural laboratories in the universe for nuclear and particle physics, neutron stars [1] have generated much effort concentrated on exploring the equation of state (EOS) of baryonic matter at low temperature and high density [2,3]. Specifically, the mass of the observed neutron stars produces a strong constraint on the behavior of EOS at supranuclear density. The most precise measurements for the neutron-star mass are determined to be less than $1.5M_\odot$ from the timing observations of radio binary pulsars [4], which has remained as the constraint on the EOS for many years. However, the existence of more massive compact stars has now been unveiled [5]. In a survey with the Arecibo telescope, an eccentric binary millisecond pulsar PSR J1903+0327 was found with an unusually high mass value $(1.74 \pm 0.04)M_\odot$ [6]. Recently, a much larger pulsar mass of $(1.97 \pm 0.04)M_\odot$ was measured using the Shapiro delay for the binary millisecond pulsar J1614-2230 [7]. These data imply a stiff EOS of strongly interacting matter at high densities, which needs to be further checked by newly developed land- and space-based observatories.

So far, there still exists considerable theoretical uncertainty on the EOS at supranuclear densities due to the poorly constrained many-body interaction, which consequently leads to very different maximum mass and radius for a β-stable neutron star. As indicated by prior studies of neutron stars based on the density-dependent relativistic Hartree-Fock (DDRHF) theory [8,9], the maximum mass predicted by the covariant density functional (CDF) calculations [10,11] lies between $2M_\odot$ and $2.8M_\odot$. The corresponding EOSs deviate remarkably from each other in the high-density region. In the center of neutron stars, the density is generally considered to be as high as 5–10 times the nuclear equilibrium (saturation) density $\rho_0 \approx 0.16\ \mathrm{fm}^{-3}$ of neutrons and protons found in laboratory nuclei. At such high density, exotica such as strangeness-bearing baryons, condensed mesons, or even deconfined quarks could come into existence [1], which may play significant roles in determining the EOS.

In addition to the maximum mass limits, the mass-radius relation of neutron stars is also constrained by the recent observations, which leads to another strong restriction to the EOS. Recently, a relatively soft EOS and symmetry energy were predicted in the vicinity of the nuclear saturation density from careful analyses for three Type-I X-ray bursters with photospheric radius expansion and three transient low-mass X-ray binaries, which leads to a relatively small neutron-star radius [12,13]. Such observations are inconsistent with several commonly used equations of state that account only for nucleonic degrees of freedom. It is argued that they could be produced by including the degrees of freedom beyond nucleons, e.g., hyperons, mesons, and quarks, or possibly by a better description of nucleonic interactions [12]. As a possible solution without exotic degrees of freedom, the relativistic mean field (RMF) model is recalibrated with a soft behavior of the symmetry energy around the saturation density [14,15].

Compared to other CDF models, significant improvements have been obtained with DDRHF theory [11,16] in describing the relativistic symmetry conservation [16–18], the consistency of the isospin dependence in nuclear shell evolution [19,20], the exotic structures [21,22], and excited modes [23]. In a previous study [9], significant contributions to the symmetry energy have been found from the Fock terms in the isoscalar σ and ω couplings, and the neutron-star properties determined by DDRHF theory were shown to be in fairly good agreement with the observational data.

In this paper, we continue the previous work along the same line and study the roles of exotica in neutron stars based on the DDRHF theory. It is generally believed that hyperons appear around twice the normal nuclear matter density in

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neutron-star matter [24–26]. The first hyperon to appear should be Λ as it is the lightest one with an attractive potential in nuclear matter. From the experimental binding energies of single-Λ hypernuclei, the potential depth of Λ in nuclear matter is estimated to be ~30 MeV [27]. Motivated by recent astrophysical observations, as a preliminary attempt, it is thus interesting to introduce the strangeness degree of freedom associated with Λ hyperon into the DDRHF theory and to investigate the corresponding neutron-star properties.

II. THEORETICAL FRAMEWORK

Within DDRHF, the baryons are described as pointlike particles and interact with each other by exchanging mesons (the isoscalar σ and ω as well as isovector ρ and π) and photons (A). The Λ hyperon ($\Lambda = uds$), whose strangeness $S = -1$, isospin $I = 0$, and spin parity $J^P = \frac{1}{2}^+$, participates only in the interactions propagated by the isoscalars, i.e., the σ and ω mesons. These interactions can be described by the following Lagrangian density:

$$\mathscr{L}_\Lambda = \bar{\psi}_\Lambda(i\gamma^\mu\partial_\mu - M_\Lambda - g_{\sigma\text{-}\Lambda}\sigma - g_{\omega\text{-}\Lambda}\gamma^\mu\omega_\mu)\psi_\Lambda, \quad (1)$$

where M_Λ denotes the mass of the Λ hyperon (ψ_Λ). From the Lagrangian density (1) the contributions to the energy functional as well as the Dirac equation for the Λ hyperon can be determined as for the nucleon [9,11,16,28].

For the β-stable stellar matter containing nucleons, Λ hyperons, electrons, and muons, the chemical equilibrium conditions require that

$$\mu_p = \mu_n - \mu_e, \quad (2)$$

$$\mu_\Lambda = \mu_n, \quad (3)$$

$$\mu_\mu = \mu_e, \quad (4)$$

where the chemical potentials μ_n, μ_p, μ_Λ, μ_μ, and μ_e are determined by the relativistic energy-momentum relation at Fermi momentum $p = k_F$ [9],

$$\mu_i = \Sigma_0(k_{F,i}) + E^*(k_{F,i}), \quad \mu_\lambda = \sqrt{k_{F,\lambda}^2 + m_\lambda^2}. \quad (5)$$

In the above expressions, i denotes the baryons, i.e., neutrons (n), protons (p), and Λ hyperons, and λ represents the leptons, i.e., electrons (e^-) and muons (μ^-). Further, combined with the baryon density conservation and charge neutrality, i.e.,

$$\rho_b = \rho_n + \rho_p + \rho_\Lambda, \quad \rho_p = \rho_\mu + \rho_e, \quad (6)$$

the ratios of baryons and leptons can be obtained from the self-consistent calculations for the stellar matter with given baryon density ρ_b. The EOS, the relation between the pressure and energy density for stellar matter, is then determined by DDRHF as well as other CDF calculations, in which the baryons interact by exchanging mesons, whereas the leptons are described as free fermions.

With the EOS of the stellar matter, the structure of a static, spherically symmetric, and relativistic star can be determined by solving the Tolman-Oppenheimer-Volkov (TOV) equations [29,30]. As in Ref. [9], the EOS in the low-density region ($\rho_b < 0.08$ fm^{-3}) will be provided by the BPS [31] and BBP [32] models. For a given central density $\rho(0)$ or central pressure $P(0)$, the input EOS leads to the unique solution of the TOV equations.

III. RESULTS AND DISCUSSIONS

In the following the theoretical calculations are systematically performed on the platform of CDF theory [11,16,28,33,34], specifically the DDRHF theory with effective interactions PKA1 [16] and PKO3 [19] and the RMF theory with NL-SH [35], PK1 [36], TW99 [37], and PKDD [36]. The details of the selected effective Lagrangians are summarized in Table I. For the RMF calculations, only the Hartree contributions are involved in the baryon-baryon interactions, whereas both Hartree and Fock terms are taken into account by DDRHF. In NL-SH and PK1, the nonlinear self-couplings of σ and ω mesons [36,38,39] are introduced to evaluate the in-medium effects of nuclear interaction. In TW99, PKDD, PKA1, and PKO3, such effects are introduced by the density dependence in meson-nucleon couplings [40,41], and the same density-dependent behaviors are utilized in the corresponding meson-Λ coupling channels; i.e., the meson-baryon coupling constants are treated as functions of baryon density ($\rho_b = \rho_n + \rho_p + \rho_\Lambda$). As proven by prior studies [9], such prescriptions on the in-medium effects are still reasonable for exploring the EOS at supranuclear density as well as in describing the neutron stars.

In the CDF calculations, if not specified, the proportions between meson-Λ and meson-nucleon couplings are fixed as $g_{\sigma\text{-}\Lambda}/g_\sigma = 0.600$ and $g_{\omega\text{-}\Lambda}/g_\omega = 0.653$ [42], and the masses of Λ hyperons, electrons, and muons are chosen to be $M_\Lambda = 1115.0$ MeV, $m_e = 0.511$ MeV, and $m_\mu = 105.7$ MeV, respectively. In the Lagrangian density (1) we neglect the strangeness-bearing baryon-baryon interactions, i.e., neglect the interactions mediated by the strange mesons (the scalar and vector ones consist of s and $\bar{s}$ quarks) in the Λ-Λ coupling channel. In contrast to the Λ-baryon interactions propagated by ordinary mesons that contain only up and down quarks, the interactions related to strange quarks still remain an open question.

With the selected CDF effective Lagrangians, we first study the equation of state for the β-stable stellar matter containing nucleons, Λ hyperons, electrons, and muons (or $N\Lambda e\mu$ for short), compared with those without Λ hyperons (or $Ne\mu$ for short). Figure 1(a) shows the pressures of neutron-star matter as a function of the baryon density ρ_b with the selected CDF effective interactions. For the $Ne\mu$ matter, there exist substantial deviations (black shaded ellipse) between the

TABLE I. Details of the selected CDF effective Lagrangians.

	Fock term	Nonlinear σ term	Nonlinear ω term	Density-dependent couplings
PKA1	yes	no	no	yes
PKO3	yes	no	no	yes
NLSH	no	yes	no	no
PK1	no	yes	yes	no
TW99	no	no	no	yes
PKDD	no	no	no	yes

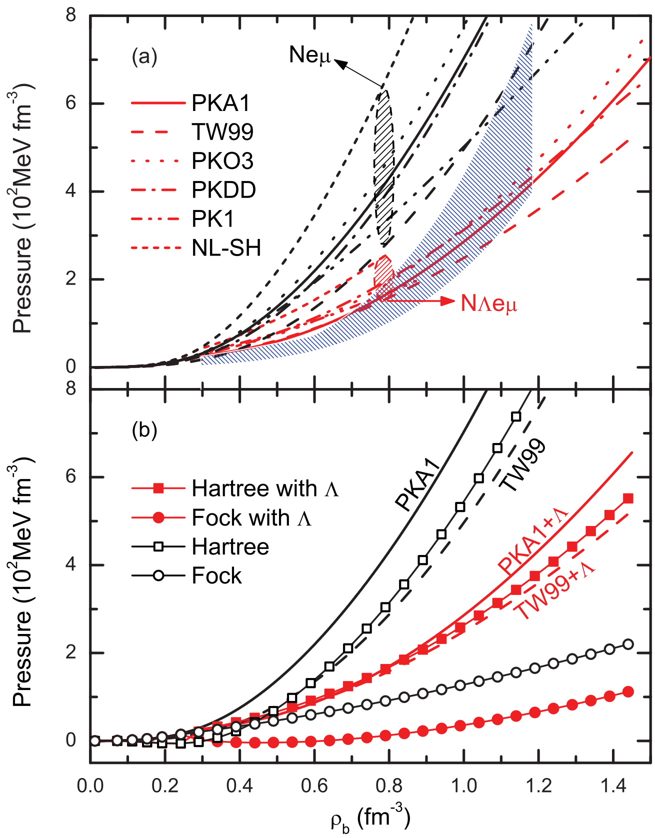

FIG. 1. (Color online) (a) The pressure as a function of the baryonic density ρ_b (fm^{-3}) with different CDF effective interactions for the stellar matter containing nucleons, Λ hyperons, electrons, and muons [red (gray) curves], compared to the one without Λ hyperons (black curves). (b) The corresponding contribution from the Hartree and Fock channels with PKA1 compared with TW99. See the text for details.

EOSs, among which NL-SH presents the hardest EOS and TW99 gives the softest one. When the Λ-hyperon degree of freedom is introduced, the EOSs become much softer above the critical density (∼0.3 fm^{-3}), where Λ hyperons start to appear in stellar matter. In addition, the deviations [red (gray) shaded ellipse] on the EOSs are considerably reduced as well. The distinctly stiff behavior of an EOS with the NL-SH effective interaction is mainly due to the absence of the nonlinear ω self-couplings [38]. It is also found that PKA1 presents a rather harder EOS than TW99 in the $Ne\mu$ matter, while with Λ hyperons PKA1 and TW99 tend to provide almost identical EOSs until $\rho_b \approx 0.8$ fm^{-3}, where the deviation emerges again.

In fact, such features of the EOS can be understood qualitatively from the chemical equilibrium between nucleons and hyperons [see Eq. (3)]. For harder EOSs, the neutron chemical potential increases more quickly as the density increases, such that more neutrons will be transferred into Λ hyperons. Because the ω-meson couplings with Λ hyperons, which play a dominant role at high density, are generally weaker than those with nucleons as repulsions, the appearance of Λ hyperons will clearly soften the EOS. Thus, the stiffer the EOS of the $Ne\mu$ matter is, the greater the effort by the Λ hyperon to soften the EOS is. When the density reaches rather large values, the ratios of Λ hyperons and nucleons become stable, so that the deviations among the effective Lagrangians appear again. However, such deviations have clearly been diminished due to the fairly large proportion of Λ hyperons at high density. Compared to the constraint [shaded area in Fig. 1(a)] suggested in Ref. [12] for cold matter, the EOSs of $N\Lambda e\mu$ matter show much better consistency with the constraint than those for $Ne\mu$ matter.

In softening the EOS, the occurrence of Λ hyperons presents substantial effects, and such effects are enhanced as the Λ abundance increases with the density. In the mean-field language, this is due to weaker Λ-meson couplings than those in the nucleonic sector, mainly the strongly reduced repulsive Λ-ω coupling, such that one may obtain rather weak repulsion from the Λ-hyperonic sector after the attractive scalar and repulsive vector balance. In this work, we neglect the strangeness-bearing Λ-Λ interactions. Similar to ordinary Λ-Λ interactions mediated and balanced by scalar σ and vector ω mesons, some additional repulsion is expected from the strange channels, which may somewhat stiffen the EOS. Notice that there still remain many mysteries in the strangeness-bearing Λ-Λ interactions, which require more efforts from both experimental and theoretical physics to clarify.

To illustrate the influence of the Fock term on the EOS for the $Ne\mu$ and $N\Lambda e\mu$ matter, the pressures of neutron-star matter with DDRHF effective interaction PKA1 and DDRMF one TW99 are replotted in Fig. 1(b) as functions of the baryon density. The contributions from the Hartree and Fock channels are shown as well. Within DDRHF, one can see that the Hartree terms provide the dominant contributions to the pressures compared to the Fock terms in both $Ne\mu$ and $N\Lambda e\mu$ matter. It is also seen that the Hartree contributions in PKA1 are nearly identical to TW99 and that the difference in the EOSs comes significantly from the Fock term in PKA1. Compared to the $Ne\mu$ matter, the occurrence of Λ hyperons remarkably suppresses the Fock contributions in the $N\Lambda e\mu$ matter. This is mainly due to the effects of ω couplings in the Fock channel. In $Ne\mu$ matter the Fock terms in the N-ω couplings contribute a fairly strong repulsion at high density, whereas in $N\Lambda e\mu$ matter the Λ-ω couplings in the Fock channel represent an attraction even at high density, which substantially softens the EOS. As a result, PKA1 and TW99 present nearly identical behavior of EOSs in the density region about 2–5ρ_0, showing better consistency with the constraint [12] than other CDF effective Lagrangians.

The symmetry energy is an important quantity for illustrating the property of asymmetric nuclear matter. In general, the energy per particle of asymmetric nuclear matter $E(\rho_b, \beta)$ can be expanded in the Taylor series with respect to the asymmetry parameter $\beta = (\rho_n - \rho_p)/(\rho_n + \rho_p)$,

$$E(\rho_b, \beta) = E_0(\rho_b) + \beta^2 E_{\rm sym}(\rho_b) + \cdots. \quad (7)$$

The function $E_0(\rho_b)$ is the binding energy per particle in symmetric nuclear matter. The empirical parabolic law in Eq. (7) is confirmed to be reasonable throughout the range of the asymmetry parameter values, especially at low density. As a reasonable approximation, one can extract the symmetry

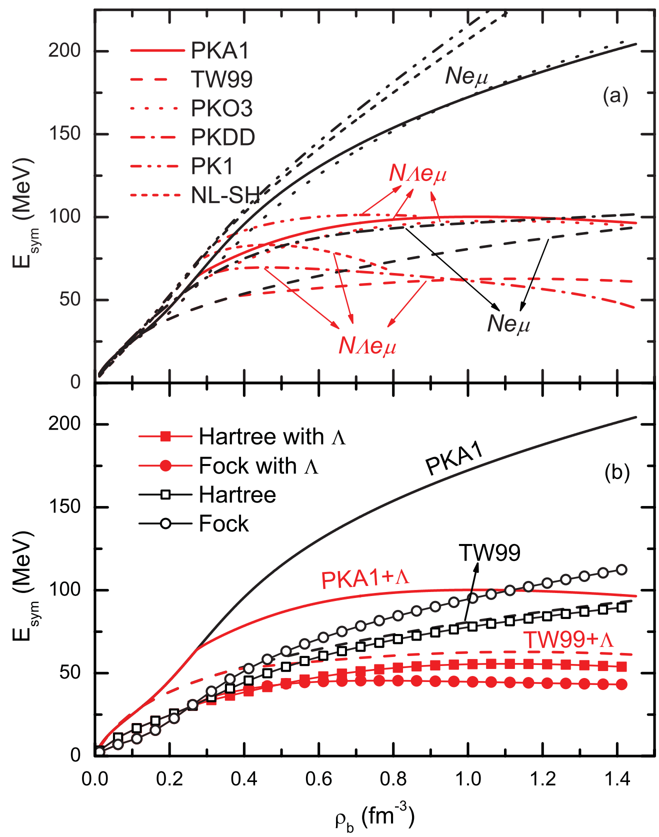

FIG. 2. (Color online) (a) The symmetry energy $E_{\rm sym}$ (MeV) as a function of the baryonic density ρ_b (fm^{-3}) with different CDF effective interactions for the stellar matter containing nucleons, Λ hyperons, electrons, and muons [red (gray) curves], as compared to the one without Λ hyperons (black curves). (b) The corresponding contribution from Hartree and Fock channels with PKA1 compared with TW99. See the text for details.

energy $E_{\rm sym}(\rho_b)$ for the β-stable stellar matter by

$$E_{\rm sym}(\rho_b) = \frac{E(\rho_b,\beta) - E_0(\rho_b)}{\beta^2}. \tag{8}$$

Figure 2(a) shows the symmetry energy of neutron-star matter as a function of the baryon density ρ_b with different CDF effective interactions. For the $Ne\mu$ matter, sizable enhancements of $E_{\rm sym}$ are seen in the high-density region with respect to $E_{\rm sym}$ at the saturation density. When the Λ hyperon is introduced, the symmetry energies become much softer, about 50% reduced at high densities. Similar to the results in Fig. 1, the deviations of $E_{\rm sym}$ among different EOSs are also reduced in the $N\Lambda e\mu$ matter. For the $Ne\mu$ matter, the Fock terms of σ and ω couplings exhibit significant contributions to the symmetry energy, which leads to a stronger density dependence in DDRHF than in DDRMF at high density [9]. While in the $N\Lambda e\mu$ matter, both Hartree and Fock contributions (e.g., in PKA1) are much reduced by Λ hyperons. In Fig. 2(b) we can see that the Hartree contributions in PKA1 are essentially identical to TW99, and correspondingly, the Fock terms provide about 2–3 times reduction as the Hartree ones do with the occurrence of Λ hyperons, leading to notably soft symmetry energy at high densities.

Taking the EOSs in Fig. 1(a) as the input, the systematic properties of neutron stars, such as the mass-radius relation, can be obtained by solving the TOV equations. Figure 3(a) shows the mass-radius relations for the neutron stars that consist of $N\Lambda e\mu$ matter (solid lines) compared to those with $Ne\mu$ matter (dashed lines). Consistent with the EOSs in Fig. 1, the inclusion of Λ hyperons results in a substantial reduction of the neutron-star mass. When Λ hyperons appear in a neutron star, the mass-radius relations deviate from those without Λ hyperons and bend down to smaller masses and radii. Close to the maximum points (symbols in Fig. 3) the mass-radius relations tend to be stable, which is also different from the calculations without Λ hyperons. This can be interpreted by the behavior of the symmetry energy at high density. In $Ne\mu$ matter the symmetry energies increase with the density almost linearly, while with the inclusion of Λ hyperons the symmetry energies become stable or even slightly decrease as the density becomes high, consistent with the mass-radius relations [see Fig. 3(a)].

Moreover, the CDF calculations for the $Ne\mu$ matter predict quite a different mass for neutron stars. However, when Λ hyperons are included, the deviations of the maximum masses among different EOSs are considerably reduced, namely, the CDF effective Lagrangians except NL-SH predict vicinal maximum mass. Comparing PKO3 with PKDD and PK1, we can see that nearly identical maximum masses are provided by PKDD and PK1 in both cases, whereas PKO3 gives a larger value in the case of the $Ne\mu$ matter. As mentioned above this can be understood well from the effects of the Fock terms in softening the EOS and thus reducing the maximum mass of neutron stars.

Extracted from Fig. 3(a), Table II shows the mass ($M_\odot$), radius (km), and central density ρ_c (fm^{-3}) for neutron stars with the maximum mass, as well as the threshold densities ρ_b^Λ (fm^{-3}) and ρ_b^μ (fm^{-3}) for Λ and muon emergence. For comparison, the results given by the calculations without Λ hyperons are shown in the last three rows. From Table II one can clearly see the mass reduction induced by the occurrence of Λ hyperons, especially in the CDF calculations with the Fock terms, i.e., the DDRHF calculations (PKA1 and PKO3), which present a mass reduction of about $0.7M_\odot$. In the RMF calculations the mass reductions range from 0.4 to 0.5 $M_\odot$, except for NL-SH, which gives a reduction of about $0.6M_\odot$.

The inclusion of Λ hyperons also has distinct effects on central density ρ_c. Among the selected effective Lagrangians PKA1 and TW99 predict the largest values of ρ_c, about 8 times the saturation density ($\sim$0.16 fm^{-3}). Compared to those excluding Λ hyperons, the central densities increase roughly 25%–38% (about 0.25–0.50 fm^{-3}) in the DDRHF calculations (PKO3 and PKA1) and about 10%–15% in the density-dependent RMF calculations (PKDD and TW99), while the central density predicted by PK1 decreases with the Λ-hyperon inclusion and NL-SH simply gives tiny changes in ρ_c.

For the radii of neutron stars with the maximum mass, distinct reductions are also found in the DDRHF calculations including Λ hyperons; e.g., PKA1 predicts a star radius of about 10.4 km, about 2 km smaller than the one without Λ hyperons, and PKO3 has a reduction of about 1 km. In the

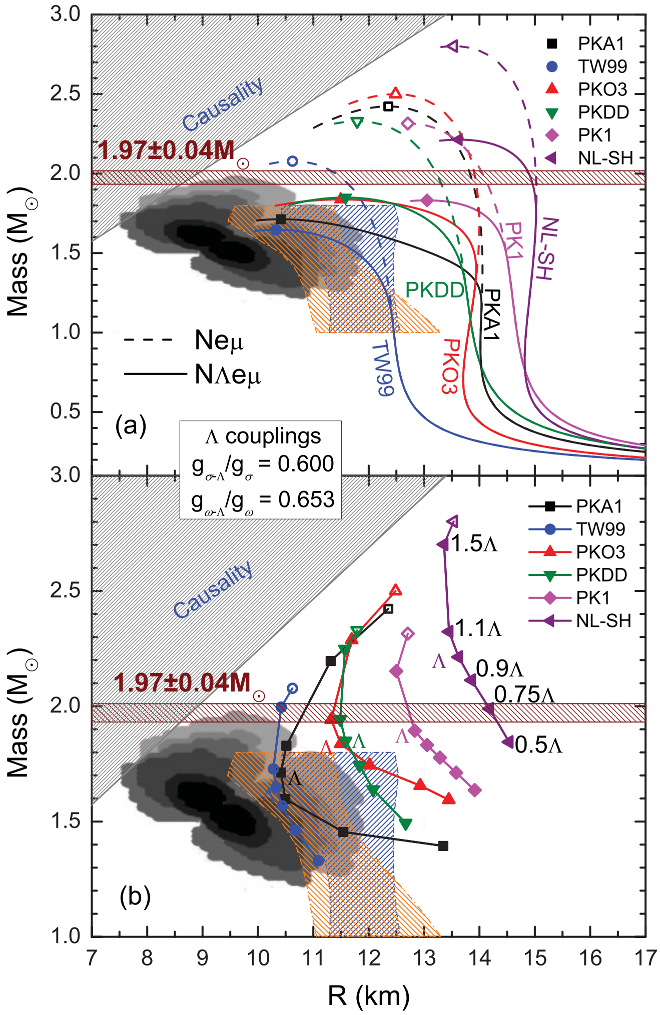

FIG. 3. (Color online) (a) The mass-radius relations for the neutron stars with Λ hyperons (solid lines) and without Λ hyperons (dashed lines). The symbols denote the neutron stars with maximum masses. The region excluded by causality is shaded. For comparison the observational constraints from three neutron stars in the binaries 4U 160-8248 (light gray/white gray), EXO 1745-248 (dark gray/gray), and 4U 1820-30 (black/black gray) in Ref. [12] are shown as the 1σ and 2σ confidence contours, and the later analyses in Ref. [13] are denoted by the shaded areas with two different models of photospheric radius. (b) The mass and radius for the neutron stars with maximum masses determined with different Λ-hyperon coupling strengths (solid symbols), compared to the ones without Λ hyperons (open symbols). See the text for details.

RMF calculations, the neutron-star radii are changed only slightly (<0.3 km) with the inclusion of Λ hyperons. Such discrepant behavior between DDRHF and RMF originates from the correlations between the radius of neutron stars and the symmetry energy. Table III shows the bulk quantities of symmetric nuclear matter at saturation density for the selected effective Lagrangians. As seen from the slope L and curvature $K_{\rm sym}$ on the symmetry energy [43], the DDRMF calculations (PKDD and TW99) present rather soft symmetry energy, and the slopes tend to decrease as density becomes high due to the negative curvature $K_{\rm sym}$. Correspondingly, small neutron-star radii are obtained in the case of $Ne\mu$ matter, especially for TW99. Similar consistence can also be seen from the calculations of DDRHF and NLRMF. In Fig. 2 it is clearly shown that the occurrence of Λ hyperons brings substantial effects in reducing the slope of the symmetry energy, mainly from the Fock channel in DDRHF. Due to such extra suppression, consistently, the reductions of the star radius are more dramatic than in the case of RMF, as proved by the results in Table II. On the other hand, it is also well demonstrated that the properties of the neutron star are strongly correlated with the values of the symmetry energy. As seen from the results in Fig. 2(a), one should notice that the symmetry energies are dramatically changed with the occurrence of Λ hyperons at high density, so that the properties of symmetry energy at normal density are not enough to describe properly the size and mass of neutron stars.

Figure 3 shows the 1σ and 2σ confidence contours for the masses and radii of three neutron stars in the binaries 4U 1608-248 (light gray/white gray), EXO 1745-248 (dark gray/gray), and 4U 1820-30 (black/black gray) [12], and a reanalyzed version recently done by another group is denoted by the shaded areas with two different models of photospheric

TABLE II. Maximum mass $M_{\rm max}$ ($M_\odot$), corresponding radii $R_{\rm max}$ (km), and central density ρ_c (fm^{-3}) for neutron stars, as well as the threshold densities ρ_b^Λ (fm^{-3}) and ρ_b^μ (fm^{-3}) of Λ and muon emergence. For comparison, the quantities for neutron stars without Λ hyperons are shown in the last three rows. The results are calculated by DDRHF with PKA1 and PKO3 and RMF with PKDD, TW99, PK1, and NL-SH.

	PKA1	PKO3	PKDD	TW99	PK1	NL-SH
$M_{\rm max}$	1.713	1.837	1.849	1.647	1.832	2.213
$R_{\rm max}$	10.425	11.495	11.583	10.333	13.048	13.633
ρ_c	1.314	1.048	1.024	1.292	0.786	0.700
ρ_b^Λ	0.272	0.284	0.322	0.368	0.306	0.282
ρ_b^μ	0.118	0.122	0.108	0.116	0.110	0.114
$M_{\rm max}$	2.423	2.500	2.329	2.078	2.315	2.802
$R_{\rm max}$	12.354	12.487	11.798	10.632	12.705	13.534
ρ_c	0.810	0.780	0.888	1.104	0.796	0.650

TABLE III. Bulk properties of symmetric nuclear matter at saturation point, i.e., the saturation density ρ_0 (fm^{-3}), binding energy per particle E/A (MeV), incompressibility K (MeV), and symmetry energy J (MeV) with its slope L (MeV) and curvature $K_{\rm sym}$ (MeV). The results are provided by the CDF effective Lagrangians PKA1, PKO3, PKDD, TW99, NL-SH, and PK1.

	ρ_0	E/A	K	J	L	$K_{\rm sym}$
PKA1	0.160	−15.83	229.96	36.02	103.50	213.23
PKO3	0.153	−16.04	262.47	32.99	83.00	116.56
PKDD	0.150	−16.27	262.18	36.79	90.21	−80.74
TW99	0.153	−16.25	240.27	32.77	55.31	−124.68
NL-SH	0.146	−16.35	355.43	36.12	113.66	79.72
PK1	0.148	−16.27	282.69	37.64	115.88	55.33

radius as well [13]. Different from other constraints such as those shown in Ref. [9], these observations seriously challenge our understanding of neutron stars, where a relatively small value of about 8.7–12.5 km is required for a $1.4M_{\odot}$ star, which is even smaller than the recent conclusion of 9.7–13.9 km from microscopic calculations based on chiral effective field theory interactions [44]. Therefore a very soft symmetry energy and EOS near and above several times the saturation density are needed. In comparison with our calculations, it is found that the mass-radius relations for the neutron stars with Λ hyperons given by PKA1 and TW99 are in perfect accordance with the observations, especially for the cases around the maximum mass. Because of a little harder EOSs at the density region of about 2–5ρ_0, PKO3 and PKDD with Λ hyperons just marginally cover the constraints, while the nonlinear RMF versions PK1 and NL-SH could not fulfill the constraints at all. In the cases without Λ hyperons, all the curves are far away from the constraints. Hence, it is strongly suggested that the exotic degrees of freedom, such as the strangeness-bearing structure, may appear inside the neutron stars. It is expected and also found in the CDF calculations that the Λ hyperon is the dominant constitution in the core of neutron star, whereas the neutron is strongly compressed to be less than 20%, from which the role of the hyperon degree of freedom is well demonstrated in neutron stars.

In Figs. 1 and 3(a) it is already shown that the Λ hyperon plays an important role in softening the EOS and reducing the neutron-star masses and radii and leads to fairly good agreements with the constraints [12,13]. One may notice that in the case of $N\Lambda e\mu$ matter none of the curves except NL-SH go through $2.0M_{\odot}$, which is constrained by another observation [7]. On the other hand, it is also found that in the calculations with Fock terms, i.e., PKA1 and PKO3, the inclusion of Λ hyperons leads to more distinct effects in reducing the neutron-star masses than those without Fock terms.

In all the above calculations the coupling strengths of Λ hyperons are fixed to $g_{\sigma\text{-}\Lambda}/g_{\sigma} = 0.600$ and $g_{\omega\text{-}\Lambda}/g_{\omega} = 0.653$. The Λ hyperon only participates in the interaction mediated by the exchange of the isoscalar σ and ω mesons, which respectively represent as strong attraction (repulsion) and repulsion (attraction) in Hartree (Fock) channels. It is well known that at high density the contributions from ω mesons play the dominant role in determining the EOS as well as the mass-radius relation for neutron stars. In contrast to the nucleonic sector, the ω-Λ Fock terms represent fairly strong attractions at high density, which remarkably reduces the repulsion from the Λ-hyperonic sector, somewhat equivalent to weakening the Λ-ω coupling strength. More distinct effects are therefore found in the DDRHF calculations with the inclusion of Λ hyperons in softening the EOS as well as reducing the neutron-star mass and radius. In fact, a similar reduction of the neutron star radius can be achieved by including the Δ resonance and adopting weaker Δ-ω coupling than the one in the nucleonic sector [45].

Here we only consider the strangeness system degree of freedom associated with Λ hyperons. Approximately and qualitatively, other strangeness-related contributions such as Σ and Ξ hyperons can effectively be taken into account by modifying the Λ-coupling strength. Figure 3(b) shows the neutron stars with the maximum mass extracted from the CDF calculation with different Λ-coupling strengths, where the Greek symbol Λ denotes the coupling strengths $g_{\sigma\text{-}\Lambda}/g_{\sigma} = 0.600$ and $g_{\omega\text{-}\Lambda}/g_{\omega} = 0.653$. That is, for 1.5Λ, for instance, the coupling strengths are taken to be $g_{\sigma\text{-}\Lambda}/g_{\sigma} = 1.5 \times 0.600$ and $g_{\omega\text{-}\Lambda}/g_{\omega} = 1.5 \times 0.653$. It is found that the neutron-star masses are substantially reduced as the Λ couplings change from 1.5Λ to 0.5Λ, roughly corresponding to the uncertainty in Λ coupling. Such behavior can be interpreted by the consistency between the EOS and Λ-coupling strength. With the weakening of Λ coupling, which is equivalent to reducing the Λ repulsion as well as the Fermi energy, more and more neutrons will be transferred into Λ hyperons, and the EOS will become softer and softer. It is also found that with decreasing Λ coupling the radii of neutron stars decrease to the minimum first and then keep increasing. The CDF calculations also show that the central densities increase to the maximum first and then begin decreasing with the reduction of Λ coupling, which is consistent with the radius evolutions. As shown in Fig. 3(b), such turning points in the mass-radius relations are rather close to the original ones (denoted by Λ), especially for PKA1, which may imply that the coupling strengths $g_{\sigma\text{-}\Lambda}/g_{\sigma} = 0.600$ and $g_{\omega\text{-}\Lambda}/g_{\omega} = 0.653$ are reasonable for the Λ coupling in stellar matter as well as in finite nuclei [42].

From Fig. 3(b) one may find that the constraint $1.97 \pm 0.04M_{\odot}$ [7] is reasonably fulfilled within the uncertainty of Λ coupling, while in Fig. 3(a) with the Λ-coupling strengths $g_{\sigma\text{-}\Lambda}/g_{\sigma} = 0.600$ and $g_{\omega\text{-}\Lambda}/g_{\omega} = 0.653$ the mass-radius relations present some discrepancies with the constraint, except for NL-SH, which indicates that the EOSs with Λ hyperons seem too soft to reproduce the constraint. One possibility for these discrepancies is the neglected strangeness-bearing Λ-Λ interactions, which may contribute additional repulsion to stiffen the EOS. The other possibility to get a stiffer EOS might be concerned with the quark degree of freedom [46,47], which may also be helpful for improving the systematics of the current mass-radius relations in small mass region.

IV. SUMMARY

In summary, we studied the general properties of neutron stars with the inclusion of strangeness-bearing Λ hyperons based on the covariant density functional theory, specifically the density-dependent relativistic Hartree-Fock theory and the relativistic mean-field theory with both nonlinear self-coupling of mesons and density-dependent meson-nucleon couplings. The inclusion of Λ hyperons in neutron-star systems shows substantial effects in softening the equation of state for the stellar matter as well as in reducing the star mass and radius, especially when the contribution of the Fock channel is included. It is shown that the properties of symmetry energy at normal density are not enough to predict the mass and radius of a neutron star. The systematical investigations on the consistence of the maximum neutron-star mass and Λ-coupling strength also indicate that exotic degrees of freedom are one of the important factors for appropriately predicting the star mass as well as the radius, in agreement with recent observations.

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