Strange hadronic matter with a weak *Y-Y* interaction

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A modified quark meson coupling (MQMC) model is extended to include Λ hyperons and Ξ hyperons. The extended model is then used to study the equation of state (EOS) for strange hadronic matter. A weak Λ-Λ interaction deduced from recent observation of ${}^{6}_{\Lambda\Lambda}$He double hypernucleus is adopted in the calculation. The resultant EOS is compared with that deduced from a strong Λ-Λ interaction. It is found that while the system with the strong Λ-Λ interaction is more deeply bound than ordinary nuclear matter due to the opening of new degrees of freedom, the system with the weak Λ-Λ interaction is rather loosely bound compared to the latter. It is necessary to introduce the strange mesons σ^* and ϕ in the MQMC model to properly describe the interaction between the hyperons in either strong or weak Λ-Λ interaction cases.

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I. INTRODUCTION

Since the first hypernucleus was seen in emulsion by Danysz and Pniewski [1] in 1953, the strangeness carried by *s* quark has opened a new dimension for studies in nuclear physics. In recent years, exploring nuclear system with strangeness, especially with large strangeness has received increasing interest. Such a system has many astrophysical and cosmological implications and is indeed interesting by itself. For instance, the core of neutron stars may contain a high fraction of hyperons [2–4]. There are two kinds of strange matter: strange quark matter and strange hadronic matter. On one hand, it has been speculated [5–8] that states of quark matter "strangelets" with large strangeness per baryon might be more stable than the normal nuclei. The experimental work searching for the strange quark matter has been going on in BNL-AGS and CERN-SPS [9–12]. Up to now, no evidence for the production of strangelets has been observed within the experimental limits. On the other hand, strange hadronic matter or hypernuclei have also been investigated [13–24]. In this case, the strange quarks are localized within individual hyperons, which are assumed to retain their identity in the bound system. As pointed out by Schaffner-Bielich and Gal [25], some early works about strange hadronic matter are incomplete, either discussing Λ matter [13,14,20] or ignoring Ξ hyperons [18] or constraining the hyperon fraction arbitrarily [19]. The correct calculation should fulfill the requirements of chemical equilibrium [22]. Up to now the inclusion of multiple units of strangeness in nuclei remains rather largely unexplored. This is because of the technical difficulty (experimental) and the uncertainty of the interactions between baryons (theoretical). Recently, Takahashi *et al.* [26] reported their observation of a ${}^{6}_{\Lambda\Lambda}$He double hypernucleus, where the Λ-Λ interaction energy $\Delta B_{\Lambda\Lambda}=1.01\pm0.20^{+0.18}_{-0.11}$ MeV is deduced from the measured data. This value is much smaller than the previous estimation $\Delta B_{\Lambda\Lambda}\simeq$4-5 MeV from the early experiments [27–29]. The Λ well depth in "Λ matter" at density $0.5\rho_0$ was estimated as $V_{\Lambda}^{(\Lambda)}\simeq20$ MeV by Schaffner *et al.* [17]. If the new value $\Delta B_{\Lambda\Lambda}=1.01$ MeV is used, $V_{\Lambda}^{(\Lambda)}\simeq5$ MeV is obtained. Up to now, almost all the theoretical studies on strange hadronic matter rely on the early estimate of the Λ-Λ interaction. It is therefore interesting to reexamine the properties of strange hadronic matter by using the new data. This is the main purpose of this work. A modified quark meson coupling (MQMC) model will be used in our discussion.

In the QMC model [30], baryon matter consists of nonoverlapping baryon bags bound by the self-consistent exchange of σ and ω mesons in the mean-field approximation (MFA). The baryon is described by the static spherical MIT bag in which quarks interact self-consistently with the above meson fields. Although it provides a simple and attractive framework to incorporate the quark structure of the nucleon in the description of nuclear system, the QMC model has a serious shortcoming. It predicts much smaller scalar and vector potentials for nucleon than obtained from relativistic nuclear phenomenology. The spin-orbit potential obtained from the QMC model is, therefore, too weak to explain the spin-orbit splittings in finite nuclei and the spin observables in nucleon-nucleus scattering. Meanwhile, the QMC model gives too large effective nucleon mass (M_N^*/M_N =0.839–0.856). Jin and Jennings [31] pointed out recently that the resulting small nucleon potentials in the QMC model stem from the assumption of fixing the bag constant at its free-space value, and that this assumption is questionable. They proposed a MQMC model, in which the bag constant depends on nuclear density. It was found that when the bag constant drops significantly in nuclear matter relative to its free-space value, the large potentials for nucleons in nuclear matter can be recovered. This is consistent with the relativistic nuclear phenomenology and finite-density QCD sum

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rules. On the other hand, Guichon *et al.* [32] improved the original QMC model to describe finite nuclei. Lu *et al.* [33] modified this version of the QMC model to consider the medium dependence of the bag constant, following Ref. [31]. We will extend this version of the MQMC model to include s quark degree of freedom and then use it to study the equation of state of strange hadronic matter by using the weak as well as the strong Λ-Λ interactions separately and compare the results in both the cases. As proposed by Schaffner *et al.* [17], we will also include the σ^* and ϕ mesons in the model to properly describe the interaction between hyperons.

Considering reactions $\Lambda+\Lambda\rightarrow\Xi^-+p$, $\Lambda+\Lambda\rightarrow\Xi^0+n$ and their reverses, one has to consider also the mixture of the cascades Ξ^- and Ξ^0 in the strange matter, besides Λs. For simplicity, we assume that Ξ^- and Ξ^0 will appear in the strange matter with equal amount. This is similar to the protons and neutrons in symmetric nuclear matter. We will, therefore, use a single symbol Ξ for these particles. In this work, we will not consider the mixture of the Σ hyperons. The reason is twofold. First, the Σ potential in the nuclear matter at saturation density is rather uncertainly predicted, ranging from completely unbound [34] to $U_\Sigma=-25\pm5$ MeV [35]. As pointed out by Balberg *et al.* [36], systems involving Σ's together with nucleons or Λ's generally will be unstable with respect to the strong decays $\Sigma N\rightarrow\Lambda N$ or $\Sigma\Lambda\rightarrow\Xi N$. Second, the Q values for the strong transitions $\Sigma N\rightarrow\Lambda N$, $\Sigma\Sigma\rightarrow\Lambda\Lambda$, $\Sigma\Lambda\rightarrow\Xi N$, and $\Sigma\Xi\rightarrow\Lambda\Xi$ are about 78, 156, 50, and 80 MeV, respectively [37]. To Pauli block these processes, we need a rather high density of Λ. On the other hand, the Q value of $\Xi N\rightarrow\Lambda\Lambda$ is only about 28 MeV.

This paper is organized as follows. The model is introduced in Sec. II. The calculated results and some discussions are presented in Sec. III.

II. THE EXTENDED MODIFIED QMC MODEL

Here we will follow the new version of the QMC model [32], which is a little different from the earlier version given by Saito and Thomas [30]. In the new version, the effective nucleon mass in nuclear matter at saturation density ρ_0 seems more reasonable than the one in the earlier version. The new version was extended later by Lu *et al.* [33] to consider the medium dependence of the bag constant. This model will be extended in this work by including Λ and Ξ hyperons in the system and an additional hyperon-hyperon (Y-Y) interaction mediated by two additional strange mesons σ^* and ϕ which couple only to hyperons. Since the system considered is symmetry for nucleons and cascades and unpolarized, there are no contributions from ρ and π mesons.

In the QMC model, baryon matter consists of nonoverlapping baryon bags bound by the self-consistent exchange of σ, ω, σ^*, and ϕ mesons in the MFA. The baryon is described by the static spherical MIT bag in which quarks interact self-consistently with above meson fields. The Dirac equation for a quark field $\psi_{i/j}$ in a bag is then given by

$$[i\gamma\cdot\partial-(m_i-g_\sigma^i\sigma-g_{\sigma^*}^i\sigma^*)-\gamma^0(g_\omega^i\omega+g_\phi^i\phi)]\psi_{i/j}=0, \tag{1}$$

where g_σ^i, g_ω^i, $g_{\sigma^*}^i$, and g_ϕ^i are the quark meson coupling constants. The subscripts i and j denote the ith quark ($i=u,d,s$) in the jth baryon ($j=N,\Lambda,\Xi$). σ, ω, σ^*, and ϕ are the mean-field values of the σ, ω (the time component), σ^* and ϕ (the time component) meson fields, respectively. m_i is the bare mass of the ith quark. It is usually assumed that the u and d quarks have the same couplings to the σ and ω mesons, which are denoted as g_σ^q and g_ω^q. And the s quark couples only to the σ^* and ϕ mesons with coupling constants $g_{\sigma^*}^s$ and g_ϕ^s. The normalized ground state for a quark in the baryons is given by

$$\psi_{i/j}(\vec{r},t)=\mathcal{N}_{i/j}\exp[-i\varepsilon_{i/j}t/R_j]\times\begin{pmatrix} j_0(x_{i/j}r/R_j) \\ i\beta_{i/j}\vec{\sigma}\cdot\hat{r}j_1(x_{i/j}r/R_j)\end{pmatrix}\frac{\chi_i}{\sqrt{4\pi}}, \tag{2}$$

where

$$\varepsilon_{i/j}=\Omega_{i/j}+R_j(g_\omega^i\omega+g_\phi^i\phi), \tag{3}$$

$$\mathcal{N}_{i/j}^{-2}=2R_j^3j_0^2(x_{i/j})[\Omega_{i/j}(\Omega_{i/j}-1)+R_jm_i^*/2]/x_{i/j}^2, \tag{4}$$

$$\beta_{i/j}=\sqrt{(\Omega_{i/j}-R_jm_i^*)/(\Omega_{i/j}+R_jm_i^*)} \tag{5}$$

with $\Omega_{i/j}=\sqrt{x_{i/j}^2+(R_jm_i^*)^2}$, χ_i being the quark spinor, and R_j the bag radius. The effective quark mass m_i^* is defined by

$$m_i^*=m_i-g_\sigma^i\sigma-g_{\sigma^*}^i\sigma^*. \tag{6}$$

The eigen-frequency $x_{i/j}$ is determined by the boundary condition at the surface:

$$j_0(x_{i/j})=\beta_{i/j}j_1(x_{i/j}).$$

The effective mass of the baryons in the matter is given by

$$M_j^*(R_j)=\frac{\sum_i n_{i/j}\Omega_{i/j}-z_0^j}{R_j}+\frac{4}{3}\pi B_jR_j^3 \tag{7}$$

with an equilibrium condition $(dM^*(R_j)/dR_j)=0$. Here B_j is the bag constant and z_0^j is a phenomenological parameter which accounts for zero-point motion and gluon fluctuation correction. $n_{i/j}$ is the quark number of type i in baryon j.

Considering the medium effect, the bag constant B_j is expressed as [31,33]

$$B_j=B_{j0}\exp\left(-\frac{4g_\sigma^{Bj}\sigma}{M_j}\right), \tag{8}$$

where g_σ^{Bj} is the coupling between σ meson and the jth bag and B_{j0} is the bag constant in free space. The bag constant depends on the baryon density through the scalar mean field σ.

The total energy per baryon at the baryon density ρ_B is given by

$$E_{tot}=\frac{1}{(2\pi)^3\rho_B}\sum_j\gamma_j\int^{k_{Fj}}d\vec{k}\sqrt{M_j^{*2}+\vec{k}^2}+\frac{1}{2\rho_B}(m_\sigma^2\sigma^2+m_\omega^2\omega^2 + m_{\sigma^*}^2\sigma^{*2}+m_\phi^2\phi^2), \tag{9}$$

where the spin-isospin degeneracy $\gamma_j=4$ for nucleons and cascades, and $\gamma=2$ for lambdas. The total baryon density ρ_B is the sum of the nucleon, Λ and Ξ densities,

$$\rho_B = \rho_N + \rho_\Lambda + \rho_\Xi . \tag{10}$$

The Fermi momentum k_{F_j} is determined by the relations $\rho_j=\gamma_j k_{F_j}^3/6\pi^2$. The ω and ϕ fields are determined by baryon number conservation, their values are expressed by

$$\omega = \frac{3g_\omega^q\rho_N + 2g_\omega^q\rho_\Lambda + g_\omega^q\rho_\Xi}{m_\omega^2} \tag{11}$$

and

$$\phi = \frac{g_\phi^s\rho_\Lambda + 2g_\phi^s\rho_\Xi}{m_\phi^2}. \tag{12}$$

The scalar mean field σ and σ^* are determined by a self-consistency condition (SCC) [22],

$$\sigma = -\frac{1}{m_\sigma^2(2\pi)^3}\sum_j \gamma_j \int^{k_{F_j}} d\vec{k}\frac{M_j^*}{\sqrt{M_j^{*2}+\vec{k}^2}}\left(\frac{\partial M_j^*}{\partial\sigma}\right)_{R_j} \tag{13}$$

and

$$\sigma^* = -\frac{1}{m_{\sigma^*}^{*2}(2\pi)^3}\sum_j \gamma_j \int^{k_{F_j}} d\vec{k}\frac{M_j^*}{\sqrt{M_j^{*2}+\vec{k}^2}}\left(\frac{\partial M_j^*}{\partial\sigma}\right)_{Rj}, \tag{14}$$

where

$$\left(\frac{\partial M_j^*}{\partial\sigma}\right)_{R_j} = -n_{q/j}g_\sigma^q S_{q/j} - \frac{16\pi g_\sigma^{Bj}R_j^3 Bj}{3M_j}, \tag{15}$$

$$\left(\frac{\partial M_j^*}{\partial\sigma^*}\right)_{R_j} = -n_{s/j}g_{\sigma^*}^s S_{s/j}. \tag{16}$$

Here $S_{i/j}$ is the scalar density of the *i*th quark in *j*th baryon:

$$S_{i/j} = \int d\vec{r}\,\overline{\psi}_{i/j}\psi_{i/j} = \frac{\Omega_{i/j}/2 + R_j m_i^*(\Omega_{i/j}-1)}{\Omega_{i/j}(\Omega_{i/j}-1) + R_j m_i^*/2}. \tag{17}$$

In the system with equal number of protons and neutrons as well as equal number of Ξ^0 and Ξ^-, the chemical equilibrium condition for the reactions $\Lambda+\Lambda \rightleftharpoons n+\Xi^0$ and $\Lambda+\Lambda \rightleftharpoons p+\Xi^-$ reads

$$2\mu_\Lambda = \mu_N + \mu_\Xi, \tag{18}$$

where

$$\mu_N = \nu_N + 3g_\omega^q\omega, \tag{19}$$

$$\mu_\Lambda = \nu_\Lambda + 2g_\omega^q\omega + g_\phi^s\phi, \tag{20}$$

$$\mu_\Xi = \nu_\Xi + g_\omega^q\omega + 2g_\phi^s\phi, \tag{21}$$

with ν_j being

$$\nu_j = \sqrt{k_{F_j}^2 + M_j^{*2}}. \tag{22}$$

Substituting Eqs. (19)–(21) in Eq. (18), we obtain the following condition for the chemical equilibrium among Ξs, Λs, and the nucleons.

$$2\nu_\Lambda - \nu_N - \nu_\Xi = 0. \tag{23}$$

One usually defines a strangeness fraction f_S as

$$f_S \equiv \frac{\rho_\Lambda + 2\rho_\Xi}{\rho_B}. \tag{24}$$

Given ρ_B and f_S, we determine ρ_N, ρ_Λ, and ρ_Ξ by Eqs. (10), (23), and (24).

III. CALCULATION AND RESULTS

We will discuss the bag constants first. The bag constant in free space B_{j0} and phenomenological parameter z_0^j are fixed by using Eq. (7) and the equilibrium condition $\partial M_j^*/\partial R_j=0$ to fit the mass M_j and radius R_{j0} of free baryons. In our calculations, we choose $R_{j0}=0.8$ fm and $m_q=0$ ($q=u,d$). For nucleon, we take $M_N=939$ MeV and then obtain $B_{N0}^{1/4}=170.28$ MeV and $z_0^N=3.273$. As for the hyperons, we assume that the values of B_{j0} are equal to the values of B_{N0} and set the *s*-quark mass $m_s=250$ MeV. Then we obtain $Z_0^\Lambda=3.117$ and $R_{\Lambda 0}=0.806$ fm by fitting free Λ mass $M_\Lambda=1116$ MeV and $Z_0^\Xi=2.857$ and $R_{\Xi 0}=0.818$ fm by fitting the free cascade mass $M_\Xi=1318.1$ MeV.

We next come to the coupling constants. As in Ref. [33], the coupling between σ field and nucleon bag is set as $g_\sigma^{BN}=2.8$. Then $g_\sigma^q=4.14$ and $g_\omega=3g_\omega^q=9.34$ are determined so as to fit the binding energy per nucleon (−15.73 MeV) and the saturation density ($\rho_0=0.15\ \mathrm{fm}^{-3}$). The effective nucleon mass $M^*/M=0.761$ obtained seems reasonable. Then the coupling between σ field and lambda bag $g_\sigma^{B\Lambda}=1.663$ is determined by fitting the energy $E_\Lambda=-28$ MeV [38,39] of one single Λ in symmetric nuclear matter at saturation density. Similarly, we have used the energy of one single Ξ in symmetric nuclear matter, $E_\Xi=-18$ MeV [40] to determine the coupling constants between σ field and Ξ bag, $g_\sigma^{B\Xi}=1.109$. And then there are two coupling constants $g_{\sigma^*}^s$ and g_ϕ^s to be determined. Following Ref. [17], we fix g_ϕ^s by using the SU(6) relation: $g_\phi^s/g_\omega^q=-\sqrt{2}$. As for the determination of the coupling constant $g_{\sigma^*}^s$, the left physical constraint, namely, the Λ-Λ interaction energy in double Λ hypernucleus $\Delta B_{\Lambda\Lambda}$ can be used. In doing so, one should do calculations for finite nuclei to adjust for $\Delta B_{\Lambda\Lambda}$. It will be very complicated in the MQMC model and will be done elsewhere. Since the main purpose of this work is to make a simple estimate of the effect from different Λ-Λ interaction strength, we will just follow the estimation made by Schaffner *et al.* [17]. Denoting the potential depth of a single nucleon in a nucleon "bath" at saturation density ρ_0 by $V_N^{(N)}$, the potential depth of a single Λ in a Λ bath at $\rho_\Lambda \simeq 0.5\rho_0$ by $V_\Lambda^{(\Lambda)}$, they obtained

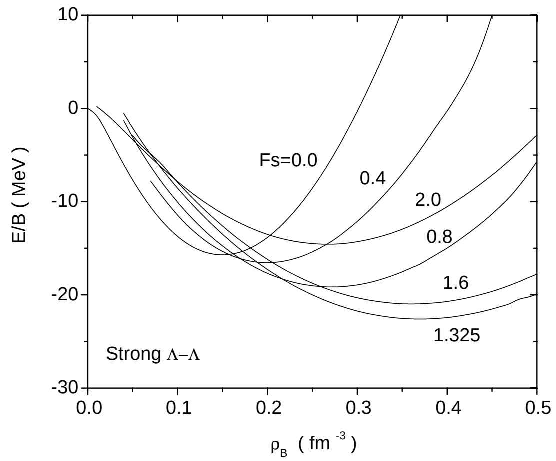

FIG. 1. Energy per baryon vs baryon density in the strange hadronic matter with various values of f_S, calculated with a strong Λ-Λ interaction.

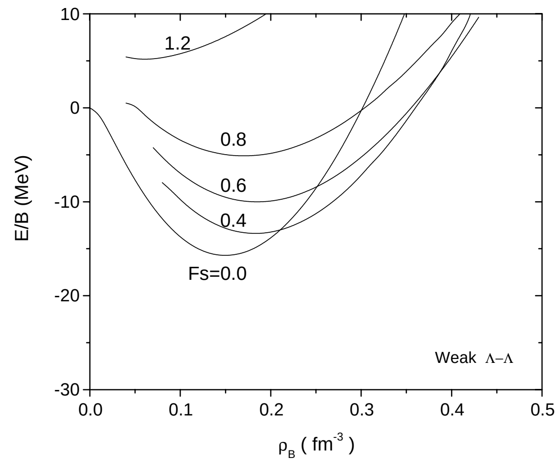

FIG. 2. Energy per baryon vs baryon density in the strange hadronic matter with various values of f_S, calculated with a weak Λ-Λ interaction.

$$\frac{V_\Lambda^{(\Lambda)}}{V_N^{(N)}}=\frac{1}{2}\frac{(1/4)V_{\Lambda\Lambda}}{(3/8)V_{NN}}\simeq\frac{1}{4}, \tag{25}$$

where the first factor of 1/2 stands for the density ratio of the two baths and the second for the statistical factors appearing in Eqs. (14a)–(14c) in Ref. [17] (a 1/4 for ΛΛ and a 3/8 for NN). From old data, $V_{\Lambda\Lambda}\equiv\Delta B_{\Lambda\Lambda}\simeq 4$–5 MeV and $V_{NN}\simeq 6$–7 MeV, we have $V_{\Lambda\Lambda}/V_{NN}\simeq 3/4$ for the last ratio. Since $V_N^{(N)}$ is about 80 MeV in relativistic mean field, we obtain $V_\Lambda^{(\Lambda)}\simeq 20$ MeV. If we take $V_{\Lambda\Lambda}\simeq 1.01$ MeV from the newest data, then $V_\Lambda^{(\Lambda)}\simeq 1/16 V_N^{(N)}\simeq 5$ MeV. The coupling constant $g_{\sigma^*}^s=8.675$ is then determined by fitting the well depth $V_\Lambda^{(\Lambda)}\simeq 20$ MeV. Since the above value is estimated according to a stronger Λ-Λ interaction, $\Delta B_{\Lambda\Lambda}\simeq 4$–5 MeV, it will be referred hereafter as strong Λ-Λ interaction. If we use the newest value $\Delta B_{\Lambda\Lambda}\simeq 1.01$ MeV, then we have $V_\Lambda^{(\Lambda)}\simeq 5$ MeV and $g_{\sigma^*}^s=2.875$. It will be referred as weak Λ-Λ interaction. The bare masses of the mesons are taken to be $m_\sigma=550$ MeV, $m_\omega=783$ MeV, $m_\rho=770$ MeV, $m_{\sigma^*}=975$ MeV, and $m_\phi=1020$ MeV.

By using the formalism presented in Sec. II and the coupling constants determined above, the saturation properties of the strange hadronic matter with different strangeness fractions f_S are studied. As usual, we would like to subtract the baryon masses in the total energy per baryon of the strange matter given by Eq. (9) and to study the binding energy per baryon expressed as

$$\frac{E}{B}=E_{tot}-M_N(1-Y_\Lambda-Y_\Xi)-M_\Lambda Y_\Lambda-M_\Xi Y_\Xi, \tag{26}$$

where Y_Λ and Y_Ξ are the Λ and cascade fractions, respectively, in the matter defined as $Y_\Lambda=\rho_\Lambda/\rho_B$ and $Y_\Xi=\rho_\Xi/\rho_B$. The binding energy per baryon E/B vs baryon density ρ_B at various strangeness fractions f_S, calculated with the strong Λ-Λ interaction, are presented in Fig. 1. It is seen that with increasing strangeness fraction f_S, the saturation curves get first deeper until a f_S value of around 1.33 is reached and then become shallower and meanwhile the saturation point moves towards high density until a value of around $\rho\simeq 0.38$ fm^{-3} is reached and then moves backwards. There is a negative minimum for each curve with f_S value from 0 to 2.0. It means that the strange hadronic matter is stable against particle emission within the region of the strange fractions considered here. The cases with $f_S=0$ and $f_S=2$ correspond to the ordinary nuclear matter and pure cascade matter, respectively, where the chemical equilibrium condition is not satisfied.

The same curves but with the weak Λ-Λ interaction are shown in Fig. 2. One can find that the situation in this case is very different from that of the strong Λ-Λ interaction case as shown in Fig. 1. It is seen that the saturation curve gets shallower and shallower with increasing strangeness fraction f_S. And there is no negative minimum in the saturation curve when f_S value is larger than about 1.0. The results indicate that the strange hadronic matter with the weak Λ-Λ interaction is less stable than the normal nuclear matter and becomes unstable when the strangeness fraction f_S is over 1.0.

To see the stability of the system against f_S, we minimize E/B with respect to ρ_B for each strangeness fraction f_S. As a function of the strangeness fraction f_S, we present the minimized E/B in Fig. 3(a), the corresponding baryon density ρ_B in Fig. 3(b), and the corresponding fractions of the Λ Y_Λ and of the cascade Y_Ξ in Fig. 3(c) for the strong (the solid curves) as well as the weak (the dashed curves) Λ-Λ interactions. The differences in two cases become more clear in these figures. With the strong Λ-Λ interaction, the strange hadronic matter is more deeply bound for most f_S values considered here than the normal nuclear matter. The most deeply bound state appears at baryon density $\rho\simeq 0.38$ fm^{-3} and with strangeness fraction $f_S\simeq 1.33$, where cascade dominates. If the Λ-Λ interaction is weak, then the strange hadronic matter with any strangeness fraction is less stable than the normal nuclear matter. The larger the strangeness fraction is, the less stable the system is. The minimized energy for each f_S increases with increasing f_S. There is no negative minimum when f_S is larger than about 1.0. In fact, even if in the strong Λ-Λ interaction case, either the interaction be-

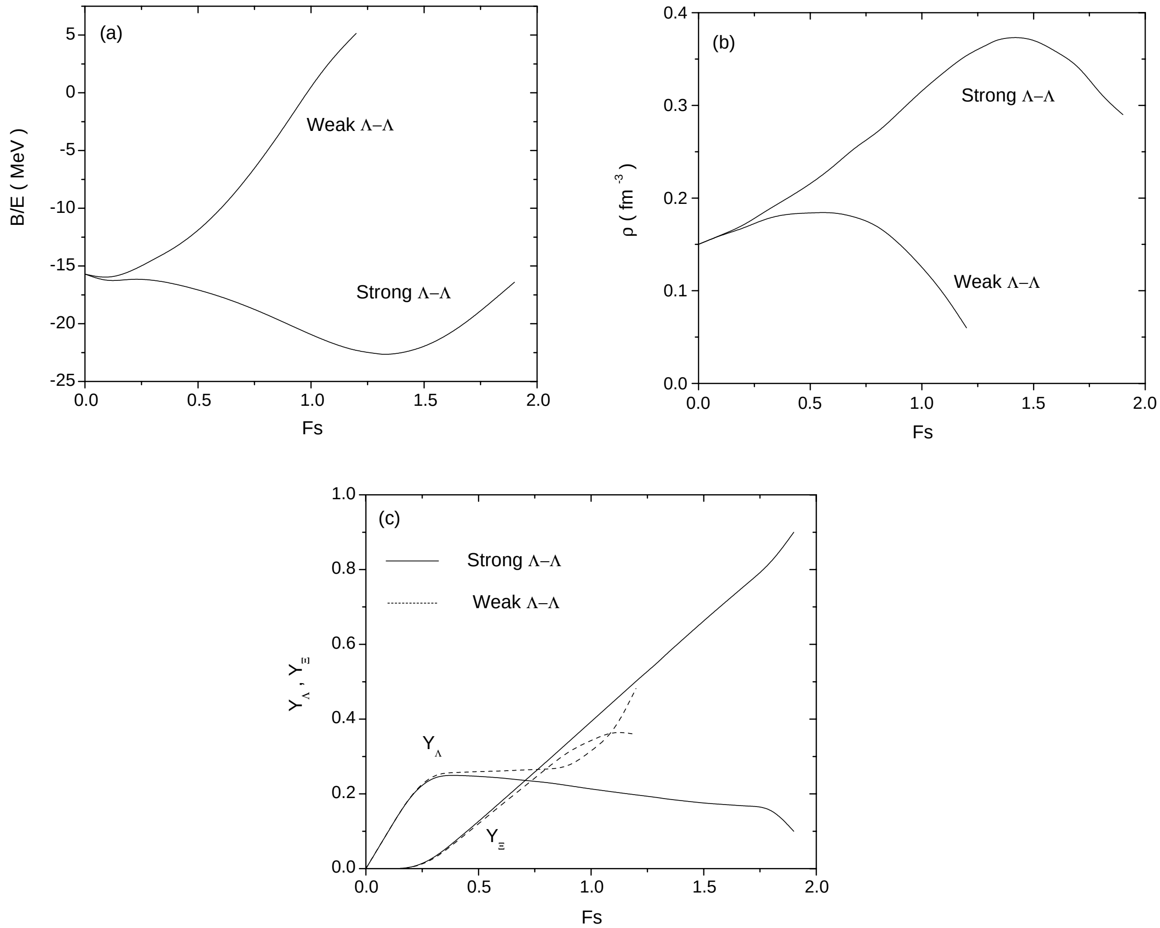

FIG. 3. (a) The minimized energy per baryon, (b) the corresponding baryon density, and (c) the corresponding λ fraction Y_Λ and cascade fraction Y_Ξ in the strange hadronic matter with the strong Λ-Λ interaction (solid curve) and the weak Λ-Λ interaction (dashed curve), as a function of strangeness fraction f_S.

tween nucleon and hyperon, V_{N-Y} or the interaction between hyperons V_{Y-Y} is still weaker than the interaction between nucleons V_{N-N}. It is the opening of the new degrees of freedom that causes the hyperons to fill the levels lower than the Fermi level of nucleons, which lowers the strange hadronic system.

In order to examine the role of the strange mesons σ^* and ϕ, the calculation of the saturation curves was also made for the system by switching off the parts of the *Y*-*Y* interaction mediated by the two strange mesons. The results are shown in Fig. 4. One can easily find that the situation in this case is between those with the strong and weak Λ-Λ interactions, i.e., the system in this case is too loosely bound compared to the one with the strong Λ-Λ interaction but too tightly bound compared to the one with weak Λ-Λ interaction. In fact, the potential $V_\Lambda^{(\Lambda)}$ of a single Λ hyperon in the Λ bath at density ρ_Λ=0.5ρ_0, in this case, is about 13.8 MeV which is much deeper than 5 MeV required by the recent experiment [26]. It is, therefore, still necessary to introduce the σ^* and ϕ mesons to describe properly the interactions between hyperons.

In summary, we have extended the MQMC model for ordinary nuclear matter to strange hadronic matter and then used the extended model to discuss the properties of strange hadronic matter. From the above discussions, we have learned that the different *Y*-*Y* interactions result in very different systems. While the system with the strong Λ-Λ interaction and in a quite large strangeness fraction region is more

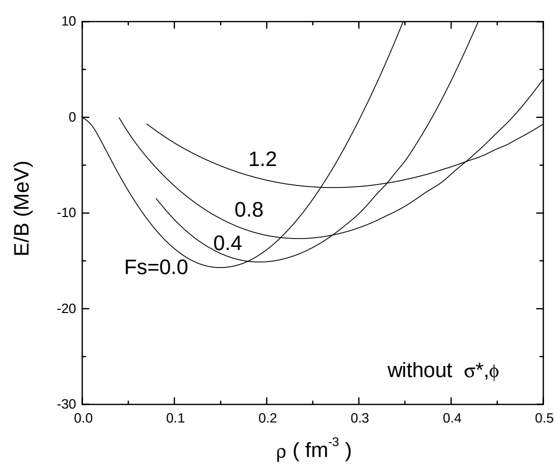

FIG. 4. Energy per baryon vs baryon density in the strange hadronic matter with various values of f_S, calculated without σ^* and ϕ mesons.

deeply bound than the ordinary nuclear matter due to the opening of the new degrees of freedom, the system with the weak Λ-Λ interaction is rather loosely bound compared to the later. In either strong or weak Λ-Λ interaction case, it is necessary to introduce the strange mesons σ^* and ϕ to describe properly the Y-Y interaction in the MQMC model. If the weak Λ-Λ interaction is reliable, then the previous discussions on strange hadronic matter and its consequences should be reexamined. The further precise measurements of double hypernuclei are desired.

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