Warm strange hadronic matter in an effective model with a weak Y-Y interaction

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An effective model is used to study the equation of state(EOS) of warm strange hadronic matter with nucleons, Λ-hyperons, Ξ-hyperons, σ\textsuperscript{*} and φ. In the calculation, a newest weak Y-Y interaction deduced from the recent observation\textsuperscript{[1]} of a \( ^6 \Lambda \Lambda \text{He} \) double hypernucleus is adopted. Employing this effective model, the results with strong Y-Y interaction and weak Y-Y interaction are compared.

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I. INTRODUCTION

Normal nuclei are made of protons and neutrons. If hyperon carrying strangeness is added into a nucleus somehow, we then obtain hypernuclei. The first hypernucleus was seen in emulsion by Danysz and Pniewski in 1953. Since then, strangeness carried by s-quark opens a new dimension for the studies in nuclear physics. In recent years, exploring nuclear system with strangeness, i.e., strange matter has received increasing interest. Such 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, resulting in a third family of compact stars which has a similar mass to neutron star but has a much smaller radius than the later. The strange matter may also be formed in relativistic heavy ion collisions. There are two kinds of strange matter: strange quark matter and strange hadronic matter. On one hand, it has been speculated that lumps of quark matter ("strangelets") with large strangeness per baryon might be more stable than the normal nuclei. The experimental work searching for strange quark matter has been going on in BNL-AGS and CERN-SPS. But unfortunately, the evidence for the production of strangelets has not yet been observed within the experimental limits. On the other hand, strange hadronic matter or hypernuclei have also been investigated. But the inclusion of multiple units of strangeness in nuclei remains rather largely unexplored yet. This is because the technical difficulty experimentally and the uncertainty of the interactions between baryons theoretically. Recently, Takahashi et al. reported their observation of a $^6_{\Lambda\Lambda}$He double hypernucleus, where the $\Lambda - \Lambda$ interaction energy $\Delta B_{\Lambda\Lambda} = 1.01 \pm 0.20^{+0.18}_{-0.11}$MeV is deduced from measured data. This value is much smaller than the previous estimation $\Delta B_{\Lambda\Lambda} \simeq 4 - 5$MeV from the early experiments. To incorporate the early strong Y-Y interaction, the $\Lambda$ well depth in "$\Lambda$ matter" at density $0.5\rho_0$ was estimated as $V_{\Lambda}^{(A)} \simeq 20$ MeV by using the Nijmegen model D. If the new value $\Delta B_{\Lambda\Lambda} = 1.01$MeV is used, the $V_{\Lambda}^{(A)} \simeq 5$ MeV is obtained. The measurement of $^4_{\Lambda\Lambda}H$ was also performed in BNL, but they did not obtain the interaction between the lambdas.

Although QCD is the fundamental theory for strong interaction, it is not available to describe strange hadronic matter directly because of its non-perturbative properties. Two kinds of effective models had been introduced. The first kind is focused on the chiral SU(3) symmetry. For example, in ref. a generalized Lagrangian which is based on the linear realization of chiral SU(3) symmetry and the concept of broken scale invariance was proposed to describe the SHM. The second kind is based upon the successful models of nuclear matter, for example, Walecka model, quark-meson coupling(QMC) model, or Furnstahl-Serot-Tang(FST) model, and adding hyperons into these models. In refs. and , two models (denoted as model 1 and model 2) which are based on a SU(3) extension of the Walecka model are suggested to deal with the weak and strong Y-Y interaction. In particular, in the model 2, in order to incorporate the early strong Y-Y interaction data, two additional mesons, namely, $\sigma^*$ and $\phi$ mesons are introduced to obtain the strong attraction between $\Lambda$ hyperons. The advantage of this treatment is that it can easily reduce to an effective
model which can explain the nuclear systems very well when the hyperons are taken away, because the coupling constants between nucleons and mesons are determined by the experimental data of nuclear system. In this sense, the effect of hyperons can be exposed explicitly. Of course, part of the second kind of models suffer from the loss of chiral SU(3) symmetry. In fact, the treatment for adding hyperons to nuclear system to study the hypernuclei, for example, Λ hypernuclei has been employed by many previous papers.

Recently, by using an extended modified quark meson coupling (MQMC) model we studied the implications of the newest Y-Y interaction in strange hadronic matter. It is found that while the system with the strong Λ − Λ interaction and in a quite large strangeness fraction region is more 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. It is interesting to check if the above remarks depend on the model used and to see what happens if the system is at finite temperature. In a previous paper, we suggested an effective model, constructed by introducing hyperons in the Furnstahl-Serot-Tang (FST) model, to study the saturation properties and stabilities of strange hadronic matter at both zero and finite temperature. In this work, we will use the extended FST model to study warm strange hadronic matter with the newest weak Y-Y interactions and then compare the results to those with previous strong Y-Y interactions. The details of this model can be found in ref. Here we only give a short description. Considering reactions, Λ + Λ → Ξ̅^- + p, Λ + Λ → Ξ^0 + n and their reverses, we take the mixture of the cascades Ξ^- and Ξ^0 in the strange matter into our model, besides lambdas. 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 used, therefore, a single symbol Ξ for these particles. Furthermore, we have also include the σ^* and φ mesons in the model to describe the interaction between hyperons, as proposed by Schaffner et al. We will not consider the mixture of the Σ hyperons in the same reason as mentioned in Ref. The paper is organized as follows. In section II, we will gives a brief description of the model. The calculated results and some discussions will be presented in section III.

II. THE EXTENDED FST MODEL

In our previous paper, the original FST model was extended by including Λ and Ξ hyperons in the system and introducing a new hyperon-hyperon interaction mediated by two additional strange mesons σ^* and φ which couple only to hyperons, just as we stated in the introduction section. Since we will study the unpolarized system, the π meson has no influence on the system. Omitting the contributions from the π meson,
we have the following Lagrangian density for the FST model.

\[ \mathcal{L}(x) = \bar{\psi}_N (i \gamma^\mu \partial_\mu - g_\omega N \gamma^\mu V_\mu - M_N + g_s N \sigma) \psi_N + \bar{\psi}_\Lambda (i \gamma^\mu \partial_\mu - g_\omega \Lambda \gamma^\mu V_\mu - g_\phi \Lambda \gamma^\mu \phi_0 - M_\Lambda + g_s \Lambda \sigma + g_{s^*} \Lambda \sigma^*) \psi_\Lambda + \bar{\psi}_\Xi (i \gamma^\mu \partial_\mu - g_\omega \Xi \gamma^\mu V_\mu - g_\phi \Xi \gamma^\mu \phi_0 - M_\Xi + g_s \Xi \sigma + g_{s^*} \Xi \sigma^*) \psi_\Xi - \frac{1}{4} G_{\mu \nu} G^{\mu \nu} + \frac{1}{2} \left( 1 + \eta \frac{\sigma}{S_0} \right) m_\sigma^2 V_\mu V^\mu + \frac{1}{4!} \zeta \left( g_\omega^2 V_\mu V^\mu \right)^2 + \frac{1}{2} \partial_\mu \sigma \partial^\mu \sigma - H_q \left( \frac{S_0^2}{S_0} \right)^{2/d} \left( \frac{1}{2d} \ln \frac{S_0^2}{S_0^2} - \frac{1}{4} \right) - \frac{1}{4} S_{\mu \nu} S^{\mu \nu} + \frac{1}{2} m_\phi^2 \phi_0^2 + \frac{1}{2} \left( \partial_\mu \sigma^* \partial^\mu \sigma^* - m_{\sigma^*}^2 \sigma^* \sigma^* \right) \right) . \]  

(1)

where the meson field operators are replaced by their mean field values: \( \phi_0, V_0, \sigma_0 \) and \( \sigma_0^* \). To derive the equation of state at finite temperature, we calculate the thermodynamic potential \( \Omega \) by using the standard technique in the field theory and statistical mechanics. The result reads

\[ \Omega = V \left\{ H_q \left[ 1 - \frac{\phi_0}{S_0} \right]^d \left( \frac{1}{d} \ln \left( 1 - \frac{\phi_0}{S_0} \right) - \frac{1}{4} \right) + \frac{1}{4} \right\} - \frac{1}{2} \left( 1 + \frac{\phi_0}{S_0} \right) m_\omega^2 V_0^2 - \frac{1}{4!} \zeta \left( g_\omega N V_0 \right)^4 - \frac{1}{2} m_\phi^2 \phi_0^2 + \frac{1}{2} m_{\sigma^*} \sigma^* \sigma^* \right\} - 2k_B T \sum_{i,k} \ln \left[ 1 + e^{-\beta (E_i^*(k) - \nu_i)} \right] + \sum_{i,k} \ln \left[ 1 + e^{-\beta (E_i^*(k) + \nu_i)} \right] , \]  

(3)

where \( \beta = 1/k_B T \) and \( V \) is the volume of the system.

\[ E_i^*(k) = \sqrt{M_i^2 + k^2} \]  

(4)

with

\[ M_i^* = M_i - g_{si} \sigma_0 - g_{s^*} \sigma_0^* (i = \Lambda, \Xi), \]  

(5)

\[ M_i^* = M_i - g_{si} \sigma_0 (i = N) \]  

(6)
We define a strangeness fraction $f_S$ where

$$f_S = \frac{\rho_{BA} + 2\rho_{B\Xi}}{\rho_B}$$

and

$$\rho_B = \rho_{BN} + \rho_{BA} + \rho_{B\Xi}.$$
III. RESULTS AND DISCUSSIONS

In numerical calculation, we adopt the same parameters as in Ref. [23] (quoted in Table 1). The symbol $S(W)$ in the parentheses denotes these coupling constants are deduced from the strong(weak) $Y-Y$ interaction. To determine the coupling constant $g_{\sigma^*\Lambda}$ and $g_{\sigma^*\Xi}$, we use the estimation made by Schaffner et. al. [18]. By using the Nijmegen model D and the method given by Millener [40], they found

$$U_{\Lambda}(\Xi) \approx \frac{1}{2} U_{\Lambda}(\Lambda)$$

(15)

at densities of $\rho_{\Xi} = \rho_0$ and $\rho_{\Lambda} = \rho_0/2$, where the notation $U_Y^{(Y')}$ stands for the potential depth for hyperon $Y$ in a "bath" of hyperon $Y'$, and

$$\frac{U_{\Lambda}(A)}{U_N^{(N)}} = \frac{1}{2} \frac{1}{3/8 V_{NN}}$$

(16)

For strong $Y-Y$ interactions, $V_{AA} \equiv \Delta B_{AA} \approx 4 - 5 \text{MeV}$ and $V_{NN} \approx 6 - 7 \text{MeV}$, we have $V_{AA}/V_{NN} \approx 3/4$. In relativistic mean field, $U_N^{(N)} \approx 80\text{MeV}$, we obtain $U_{\Lambda}(\Xi) \approx U_{\Xi}(\Xi) \approx 40\text{MeV}$. But for weak $Y-Y$ interaction, $\Delta B_{AA} \approx 1.01\text{MeV}$, we have $U_{\Lambda}(\Xi) \approx U_{\Xi}(\Xi) \approx 10\text{MeV}$, and $g_{\sigma^*\Lambda}(W) = 5.46$, $g_{\sigma^*\Xi}(W) = 11.39$.

Besides these, we set $g_{\omega\Lambda}/g_{\omega N} = 2/3$, $g_{\omega\Xi}/g_{\omega N} = 1/3$, according to the OZI rule [37] and used the quark model relationships $g_{\phi\Xi} = 2g_{\phi\Lambda} = -2\sqrt{2}g_{\omega N}/3$. The bare masses of baryons and mesons are $M_N = 939 \text{MeV}$, $M_{\Lambda} = 1116 \text{MeV}$, $M_{\Xi} = 1318.1 \text{MeV}$, $m_\omega = 783 \text{MeV}$, $m_{\sigma^*} = 975 \text{MeV}$ and $m_\phi = 1020 \text{MeV}$.

We will discuss the Helmholtz free energy $F$ of the strange hadronic matter first. As usually, we subtract the

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**Fig. 1**: Free energy per baryon versus baryon density in the strange hadronic matter with various values of strangeness fraction and at temperature $T = 6\text{MeV}$, calculated with a strong $\Lambda - \Lambda$ interaction.
baryon masses in the free energy per baryon of the strange matter.

\[
\frac{F}{B} = \left( \frac{F}{B} \right)_{\text{tot}} - M_N(1 - Y_{\Lambda} - Y_{\Xi}) - M_{\Lambda}Y_{\Lambda} - M_{\Xi}Y_{\Xi}.
\]  

(17)

where \( Y_{\Lambda} = \rho_{BA}/\rho_B \) and \( Y_{\Xi} = \rho_{B\Xi}/\rho_B \) are the hyperon fractions in the matter. In Fig.1, we have plotted the free energy per baryon versus the baryon density of the matter with various strangeness fractions at temperature \( T = 6\, \text{MeV} \), calculated with the old strong Y-Y interactions. The outstanding feature is that with the increasing strangeness fraction, the saturation curves become deeper first and then shallower. The lowest minimum occurs around \( f_S = 1.3 \). The corresponding saturation density increases from \( 0.148 \, \text{fm}^{-3} \) for ordinary nuclear matter \( (f_S = 0) \) to a maximum value \( \sim 0.56 \, \text{fm}^{-3} \) at \( f_S \approx 1.3 \) and then decreases. We also note that the F/B curve for any value of \( f_S \) has a negative minimum. It means that systems at \( T = 6\, \text{MeV} \) and with any combination satisfying constraint Eq.(12) will be stable against particle emission. The Fig.2 shows the same curves as in Fig.1 but calculated with the newest weak Y-Y interactions. Due to the weakness of the Y-Y interactions used in this case, the saturation curves become shallower and shallower with increasing strangeness fraction \( f_S \) except at very small \( f_S \) value around 0.1. For the \( f_S \) value larger than about 1.25, there is no negative minimum in the curve. It means that the system will no longer be stable in this region.

To see the stability of the system against \( f_S \), we minimize the \( F/B \) with respect to \( \rho_B \) at each strangeness fraction \( f_S \) for both of strong and weak Y-Y interactions, leaving out the unstable points near zero density. As a function of the strangeness fraction \( f_S \), we present in Fig.3(a) the minimized \( F/B \), in Fig.3(b) the corresponding baryon density \( \rho_B \). In order to examine the role of the strange mesons, we have also presented...
FIG. 3: (a) The minimized free energy per baryon in the strange hadronic matter; (b) The baryon density corresponding to the minimized free energy presented in (a), as a function of strangeness fraction $f_S$.

the results without $\sigma^*$ or without both of $\sigma^*$ and $\phi$ mesons. One can see that for the strong Y-Y interactions, the minimum free energy which is much deeper than the that of the ordinary nuclear matter ($f_S = 0$) appears around $f_S = 1.3$, where the system has almost the highest density. It means that compared with the ordinal nuclear matter the system becomes more stable. On the contrary, for the weak Y-Y interactions, the minimum free energy which is only a little deeper than the ordinary nuclear matter case appears around $f_S = 0.1$. After this point, the free energy increases monotonously as baryon density increases and becomes larger than the value for the ordinary nuclear matter when $f_S > 0.45$. It means that the strange hadronic matter with weak Y-Y interactions has at most the comparable stability to the ordinary nuclear matter in small strangeness fraction $f_S$ region and becomes less stable than the ordinary nuclear matter in large $f_S$ region. If the $\sigma^*$ and $\phi$ meson fields are switched off, then the curve coincides with the weak case in small $f_S$ region and becomes deeper than the curve for weak case in large $f_S$ region. The curve without the $\sigma^*$ only grows very quickly with the strangeness fraction. It means that the $\sigma^*(\phi)$ meson gives rise the attractive(repulsive) interaction between hyperons. The above situation is quite similar to that in the MQMC model [29]. It means that the above consequence in not model dependent.

To see the situation of the strange hadronic matter at different temperature, we present in Fig.4 the free energy at saturation point verses temperature for the matter with the strong Y-Y interaction at different strangeness fractions. One can learn that the matter with different strangeness fraction has different limit temperature $T_l$, above which the system become unstable, because the $F/B - \rho$ curves become monotonous and have no
FIG. 4: Free energy per baryon at saturation point for the matter with different $f_S$ as a function of temperature, calculated with a strong Y-Y interaction.

FIG. 5: The same curves as in Fig.4 but calculated with a weak Y-Y interaction.
minimum when $T > T_1$. The highest limit temperature appears around $f_S = 1.3$ where the system is most stable. Fig.5 shows the same curves as in Fig.4 but with the weak Y-Y interactions. One can see that the highest limit temperature appears around $f_S = 0.1$ where the system is most stable in this case.

Finally, we discuss the EOS by plotting the pressure-density ($p - \rho_B$) isotherms. We show in Fig.6 the $p - \rho_B$ isotherms of the strange hadronic matter at $f_S = 0.5$ and with various temperature. The curve for low temperature exhibits the same typical shape as given by the Van der Waals interaction, i.e., there is an unphysical region where the pressure decreases with increasing baryon density. An inflection point appears around $T = 12\text{MeV}$. The situation is quite similar to the liquid-gas phase transition in ordinary nuclear matter\textsuperscript{39}. Fig.7 shows the same curves as in Fig.6 but with $f_S = 1.3$. In this case, the inflection point appears around $T = 6\text{MeV}$. This again indicates the system with large strangeness fraction is less stable than the one with small strangeness fraction when the Y-Y interaction is weak. On contrary, in the strong Y-Y interaction, the inflection point appears at a temperature a little higher than 12 MeV for $f_S = 0.5$ and around 25 MeV for $f_S = 1.3$ (see Ref.\textsuperscript{35}).

In summary, we have extended an effective model describing strange hadronic matter to finite temperature and then used it to discuss the properties of multi-hyperon nuclear matter at finite temperature. It is found the strange hadronic matter with different Y-Y interactions behaves very different. While the system with the strong Y-Y interactions and in a quite large strangeness fraction region is more stable than the ordinary nuclear matter, the system with the weak Y-Y interactions is less stable than the later. This conclusion is not
model dependent and true for both zero and finite temperature. If the weak $\Lambda - \Lambda$ interaction is reliable, then the previous studies on strange hadronic matter and its consequences should be reexamined. In particular, if one hope to extend above discussions from infinite strange hardronic matter to finite hypernuclei, the Coulomb interaction must be considered[? ]. It is therefore interesting to perform further precise measurements of double hypernuclei.

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Fig. 3 (c)