Hypernuclei and dense matter in RMF model with a chiral SU(3) potential

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Abstract. We present a chiral $\mathrm{SU}_f(3)$ RMF model (SCL3-RMF) with a chiral potential derived from the strong coupling limit of lattice QCD. In SCL3-RMF, experimental data of normal nuclei, Λ hypernuclei and Σ^- atoms are well described, and the EOS in symmetric nuclear matter is softened ($K \simeq 220$ MeV) as in the empirical ones by the hidden strange meson. We discuss the effects of strangeness degrees of freedom in neutron stars, and find that estimated neutron star maximum mass is underestimated when we include hyperons.

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INTRODUCTION

In constructing the dense matter equation of state (EOS) [1, 2], it is desired to respect both chiral symmetry and hypernuclear physics [3]. In dense matter, strangeness is expected to play a decisive role and the partial restoration of chiral symmetry would modify the hadron properties.

For chiral symmetry, we have recently developed a chiral SU(2) symmetric RMF model (SCL-RMF) [4] with a logarithmic sigma potential in the form of $-\log\sigma$, which is derived from the strong coupling limit (SCL) of the lattice QCD [5]. In this model, the energy density in vacuum at zero temperature is evaluated as,

$$U_\sigma = -a\log(\det MM^\dagger) + \frac{b}{2}\mathrm{tr}(MM^\dagger) - c\,\sigma \sim -a_\sigma \log\sigma + \frac{b_\sigma}{2}\sigma^2 - c_\sigma\,\sigma$$

where M denotes the SU(2) meson matrix, $M = (\sigma + i\pi\cdot\tau)/\sqrt{2}$. In SCL-RMF, we can explain not only saturation properties of symmetric nuclear matter EOS, but also bulk properties of finite nuclei.

From a viewpoint of hypernuclear physics, it is necessary to extend this model to a chiral SU(3) symmetric one. We have recently developed a chiral SU(3) SCL-RMF (SCL3-RMF), which includes both chiral symmetry and hypernuclear physics information [6]. We determine hyperon-meson coupling constants in SCL3-RMF by fitting existing data. Several model parameters are determined by fitting meson and baryon masses. We can reproduce the separation energies of single Λ hypernuclei (S_Λ) and the $\Lambda\Lambda$ bond energy ($\Delta B_{\Lambda\Lambda}$) in ${}^{6}_{\Lambda\Lambda}\mathrm{He}$ by choosing the coupling constants appropriately in a reasonable parameter range. The EOS of symmetric matter is found to be softened by the scalar meson with hidden strangeness, $\zeta = \bar{s}s$, which couples with σ through the determinant interaction.

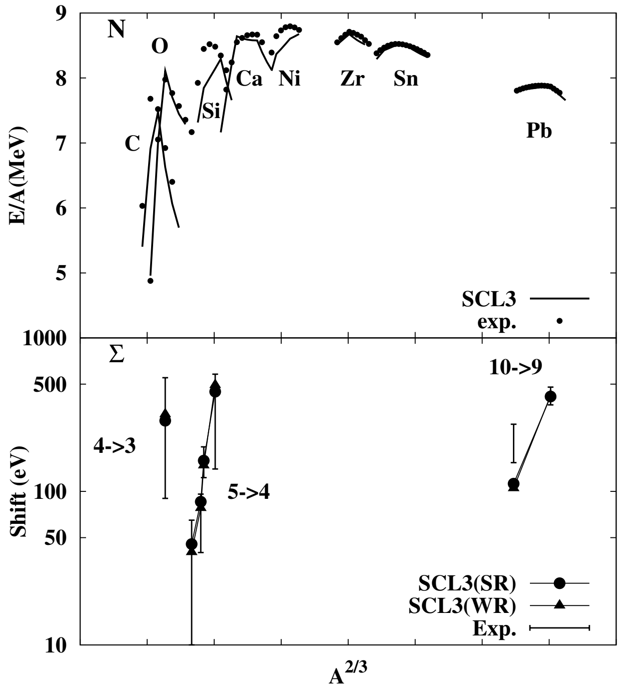

FIGURE 1. Binding energy of normal nuclei, and atomic shift of Σ^-. All parameters are determined by fitting these experimental data and the data for Λ shown in Fig. 2.

In applying SCL3-RMF to neutron star matter, it is essential to consider isovector interaction, since n/p ratio in neutron star matter is very different from that in symmetric matter or existing nuclei. While the isovector-vector meson (ρ meson) is responsible to the symmetry energy and included in RMF, the isovector-scalar meson (a_0) is usually neglected. The a_0 meson effect in finite nuclei tends to be canceled by the ρ meson after tuning $g_{\rho B}$ to fit binding energies of existing nuclei. In dense matter, it may be possible to find some differences whether a_0 meson is included or not.

In this work, we apply the chiral SU(3) RMF (SCL3-RMF) to neutron star matter, and discuss the properties of neutron star matter EOS. We also investigate the role of the a_0 meson in dense matter.

MODEL DESCRIPTION

In this paper, we adopt the SCL3-RMF Lagrangian [6], and we treat a_0 meson explicitly,

$$\begin{aligned}\mathscr{L} =&\mathscr{L}_{\text{Free}}(\psi_i, \bar{\psi}_i, a_0, \omega, \rho, \phi) + \frac{1}{2}\left(\partial_\mu \sigma \partial^\mu \sigma + \partial_\mu \zeta \partial^\mu \zeta\right) - V_\chi(\sigma, \zeta) + \frac{D_\omega}{4}\omega^4 \\ &- \sum_i \bar{\psi}_i \left[g_{\sigma i}\sigma + g_{\zeta i}\zeta + g_{a_0 i} a_0 + \gamma_\mu \left(g_{\omega i}\,\omega^\mu + g_{\rho i}\,\rho^\mu + g_{\phi i}\,\phi^\mu\right)\right]\psi_i + \mathscr{L}_{\text{EM}}\ . \qquad (1)\end{aligned}$$

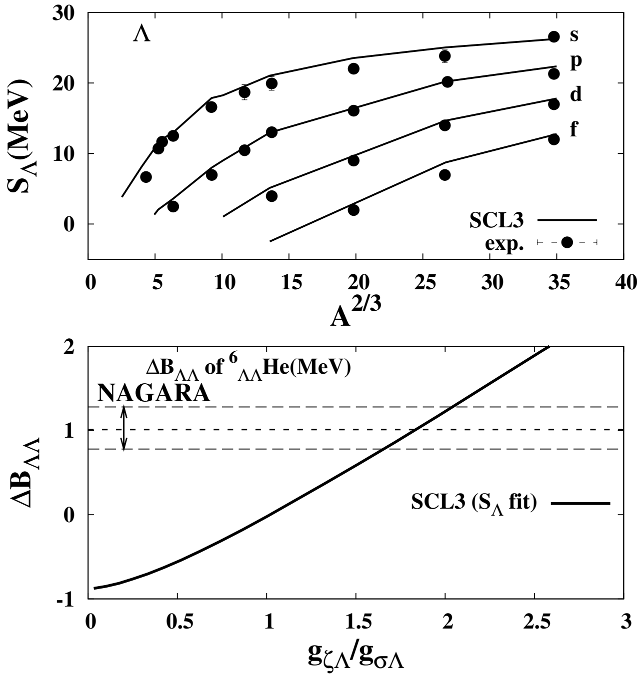

FIGURE 2. Separation energy of Λ (S_Λ) in Λ hypernuclei and the bond energy ($\Delta B_{\Lambda\Lambda}$) in ${}^{6}_{\Lambda\Lambda}$He.

The chiral SU(3) potential V_χ is obtained as an extension from the chiral SU(2) potential [4], and we introduce the determinant interaction reprensenting the $U_{\rm A}(1)$ anomaly,

$$\begin{aligned} V_\chi =& -a_\sigma \log\det\left(M^\dagger M\right) + \frac{1}{2}b_\sigma \mathrm{tr}\left(M^\dagger M\right) - c_\sigma\sigma - c_\zeta\zeta + d\left(\det M + \det M^\dagger\right) \\ =& \frac{1}{2}m_\sigma^2\varphi_\sigma^2 + \frac{1}{2}m_\zeta^2\varphi_\zeta^2 + \xi_{\sigma\zeta}\varphi_\sigma\varphi_\zeta - 2a_\sigma f_{\rm SCL}(\varphi_\sigma/f_\pi) - a_\sigma f_{\rm SCL}(\varphi_\zeta/f_\zeta)\ , \end{aligned} \tag{2}$$

$$f_{\rm SCL}(x) = \log(1-x) + x + \frac{x^2}{2}\ , \quad \varphi_\sigma = f_\pi - \sigma\ , \quad \varphi_\zeta = f_\zeta - \zeta\ . \tag{3}$$

Some of the parameters in SCL3-RMF are determined from hadron masses. For vector couplings, we assume SU$_f$(3) symmetric form,

$$\mathscr{L}_{\rm BM} = \sqrt{2}\left\{g_s\,\mathrm{tr}\,(M)\,\mathrm{tr}\,(\bar{B}B) + g_1\,\mathrm{tr}\,(\bar{B}MB) + g_2\,\mathrm{tr}\,(\bar{B}BM)\right\}\ . \tag{4}$$

and then hyperon–vector meson couplings are given as

$$g_{\omega\Lambda} = \frac{5}{6}g_{\omega N} - \frac{1}{2}g_{\rho N},\ \ g_{\phi\Lambda} = \frac{\sqrt{2}}{3}\left(g_{\omega N} + 3g_{\rho N}\right)\ , \tag{5}$$

$$g_{\omega\Sigma} = g_{\rho\Sigma} = \frac{g_{\phi\Xi}}{\sqrt{2}} = \frac{1}{2}(g_{\omega N} + g_{\rho N})\ , \tag{6}$$

$$g_{\omega\Xi} = g_{\rho\Xi} = \frac{g_{\phi\Sigma}}{\sqrt{2}} = \frac{1}{2}(g_{\omega N} - g_{\rho N})\ . \tag{7}$$

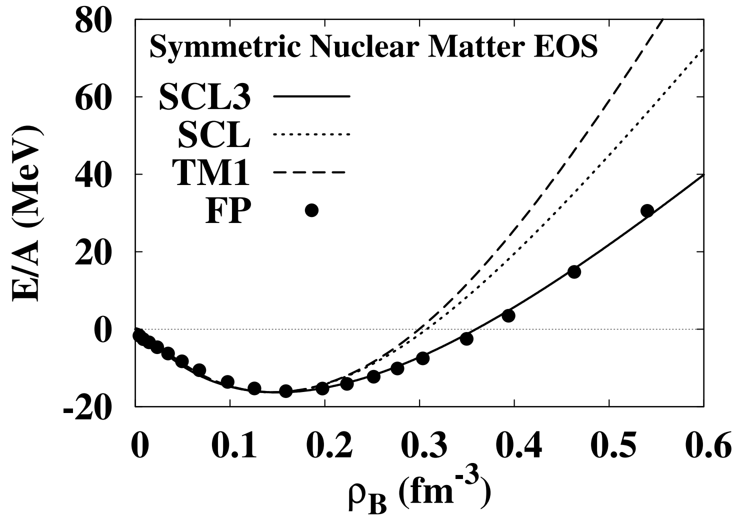

FIGURE 3. Symmetric nuclear matter EOS of TM1, chiral SU(2) ver. and chiral SU(3) one.

Here, parameters in this model are $g_{\omega N}$, $g_{\rho N}$, $g_{a_0 B}$, $g_{\sigma Y}$, $g_{\zeta Y}$, D_ω and m_σ. These parameters are determined by fitting the symmetric nuclear matter saturation point, binding energies of normal nuclei, and hypernuclear data such as S_Λ and $\Delta B_{\Lambda\Lambda}$.

After fitting these data, neutron star matter EOS is computed under the β-equilibrium and charge neutrality conditions. With this EOS, we calculate neutron star mass by solving the TOV equation and examine whether the results are supported by observed data or not.

RESULTS

In Figs. 1 and 2, we show the calculated results of binding energies in SCL3-RMF. We find that SCL3-RMF can explain experimental data of B/A and charge rms radii of normal nuclei, separation energies (S_Λ) and the bond energy ($\Delta B_{\Lambda\Lambda}$) of Λ hypernuclei, and atomic shift of Σ^- (Σ hyperatom) in a reasonable parameter range. One exception is $g_{\rho\Sigma}$, which we have to reduce from the SU$_f(3)$ relation. EOS of symmetric nuclear matter gets softer than TM model [7] or SCL-RMF (SU$_f(2)$) [4] and it is in good agreement with Friedmann–Pandharipaunde EOS [11], as shown in Fig. 3. Here, we briefly show the case without a_0 meson ($g_{aN} = 0$), and we can reproduce these data equivalently well with the a_0 meson.

After fixing the parameters, we calculate neutron star matter EOS with the same parameter. We show the results in Fig. 4. we find that smaller E/V even in high density reflects smaller incompressibility of this model. We also realize that a_0 meson effect is very small even at high ρ_B. The maximum mass of neutron stars in SCL3-RMF is around 1.65 $M_\odot$ as shown in Fig. 5.

Now we introduce the Λ degree of freedom explicitly, and calculate neutron star matter EOS with parameter sets determined from Λ hypernuclear data. As shown in

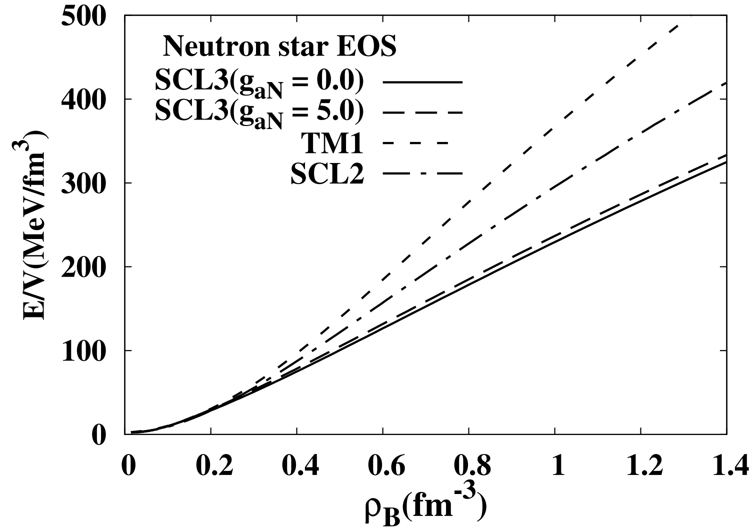

FIGURE 4. Calculated neutron star matter EOS with TM1, SCL-RMF ($\mathrm{SU}_f(2)$) and SCL3-RMF ($\mathrm{SU}_f(3)$). We also show calculated results including a_0 meson explicitly.

Fig. 5, calculated neutron star maximum mass is around $1.34\mathrm{M}_\odot$, and it underestimates the observed mass with high precision, 1.44 $M_\odot$. We can note that a_0 meson also has almost no effect for neutron star mass as in the case of EOS.

SUMMARY AND DISCUSSION

In this work, we have investigated the effects of the strangeness and a_0 degrees of freedom in an RMF model with a chiral SU(3) potential derived from the strong coupling limit of lattice QCD.

First, we have demonstrated that the present SCL3-RMF can well describe the binding energies of normal nuclei , Λ hypernuclei, and Σ^- atoms. Next, we have shown that strangeness may soften the EOS of symmetric nuclear matter not only at high densities but also at around ρ_0. This softening comes from the determinant interaction, which generates the coupling of σ and $\zeta(=\bar{s}s)$ mesons [6]. We have also investigated the role of the isovector-scalar (a_0) meson. We find there is almost no signal of the a_0 meson in the results on the EOS at high densities and neutron star maximum mass, if we fix model parameters so as to reproduce experimental data. Finally, we have examined the effects of Λ hyperons in neutron star matter. The calculated neutron star maximum mass is around $1.3M_\odot$, which is lower than the observed mass, with Λ is included with the parameter set determined from Λ hypernuclear data.

We find that the symmetric nuclear matter EOS around ρ_0 is in good agreement with the variational calculation result (Friedman–Pandaripaunde EOS), but the present EOS is too soft at high ρ_B to support large neutron star masses. Thus we have to introduce re-stiffening mechanisms at high ρ_B. For example, $\sigma\omega$ coupling [8, 9] leads stiff EOS at high ρ_B. The experimental data [10] suggest vector meson mass reduction in nuclear

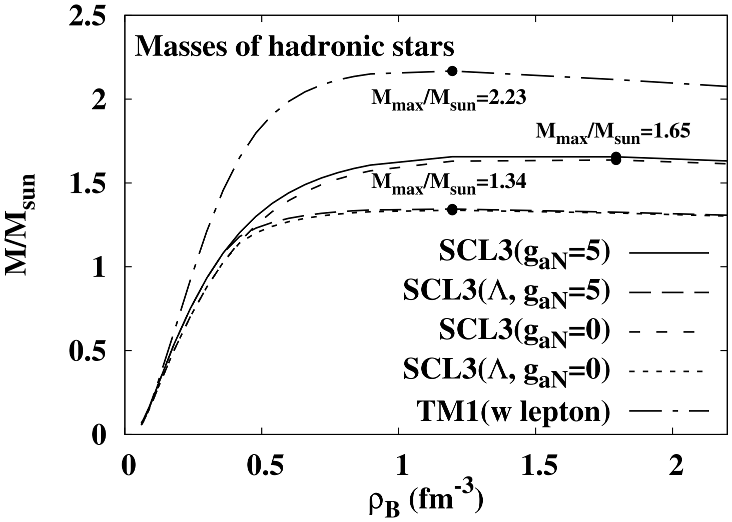

FIGURE 5. Calculated neutron star masses as a funciton of the central density in TM1, SCL-RMF ($SU_f(2)$), and SCL3-RMF ($SU_f(3)$).

medium, which may be caused by the partial restoration of chiral symmetry. From this point of view, we may solve this problem by taking this coupling partially.

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