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Equation of state of isospin-asymmetric nuclear matter in relativistic mean-field models with chiral limits

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Abstract

Using in-medium hadron properties according to the Brown–Rho scaling due to the chiral symmetry restoration at high densities and considering naturalness of the coupling constants, we have newly constructed several relativistic mean-field Lagrangians with chiral limits. The model parameters are adjusted such that the symmetric part of the resulting equation of state at supra-normal densities is consistent with that required by the collective flow data from high energy heavy-ion reactions, while the resulting density dependence of the symmetry energy at sub-saturation densities agrees with that extracted from the recent isospin diffusion data from intermediate energy heavy-ion reactions. The resulting equations of state have the special feature of being soft at intermediate densities but stiff at high densities naturally. With these constrained equations of state, it is found that the radius of a $1.4M_\odot$ canonical neutron star is in the range of 11.9 km $\leqslant$ R $\leqslant$ 13.1 km, and the maximum neutron star mass is around $2.0M_\odot$ close to the recent observations.
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1. Introduction

The Equation of State (EOS) of isospin asymmetric nuclear matter plays a crucial role in many important issues in astrophysics, see, e.g., Refs. [1–3]. It is also important for understanding both the structure of exotic nuclei and the reaction dynamics of heavy-ion collisions, see, e.g., Ref. [4]. Within the parabolic approximation, the energy per nucleon in isospin asymmetric nuclear matter can be written as $E/A = e(\rho) + E_{\rm sym}(\rho)\delta^2$ where $e(\rho)$ is the EOS of symmetric nuclear matter, the $E_{\rm sym}(\rho)$ is the symmetry energy and $\delta = (\rho_n - \rho_p)/\rho$ is the isospin asymmetry. Both the $e(\rho)$ and the $E_{\rm sym}(\rho)$ are important in astrophysics although maybe for different issues. For instance, the maximum mass of neutron stars is mainly determined by the EOS of symmetric nuclear matter $e(\rho)$ while the radii and cooling mechanisms of neutron stars are determined instead mainly by the symmetry energy $E_{\rm sym}$ [1,5]. The nuclear physics community has been trying to constrain the EOS of symmetric nuclear matter using terrestrial nuclear experiments for more than three decades, see, e.g., [6], for a review. On the other hand, a similarly systematic and sophisticated study on the density dependence of the symmetry energy $E_{\rm sym}$ using heavy-ion reactions only started about ten years ago stimulated mostly by the progress and availability of radioactive beams [7]. Compared to our current knowledge about the EOS of symmetric nuclear matter, the symmetry energy $E_{\rm sym}$ is still poorly known especially at supra-normal densities [8] given the recent progress in constraining it at densities less than about $1.2\rho_0$ using the isospin diffusion data from heavy-ion reactions [9–11].

The aim of this work is to investigate the EOS of isospin asymmetric nuclear matter within the relativistic mean-field

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(RMF) model with in-medium hadron properties governed by the BR scaling. From the point of view of hadronic field theories, the symmetry energy is governed by the isovector meson exchange. Studying in-medium properties of isovector mesons is thus of critical importance for understanding the density dependence of the symmetry energy. We first construct model Lagrangians respecting the chiral symmetry restoration at high densities. The model parameters are adjusted such that the symmetric part of the resulting EOS at supra-normal densities is consistent with that required by the collective flow data from high energy heavy-ion reactions [6], while the resulting density dependence of the symmetry energy at sub-saturation densities agrees with that extracted from the recent isospin diffusion data from intermediate energy heavy-ion reactions [9–11]. The constrained EOS is then used to investigate several global properties of neutron stars.

2. Relativistic mean-field models with chiral limits

In-medium properties of the isovector meson ρ can be studied through the special symmetry breaking and restoration. The local isospin symmetry in the Yang–Mills field theory, where the ρ meson may be introduced as a gauge boson of the strong interaction, can serve as a possible candidate to study the in-medium properties of ρ meson. However, since πN interactions actually dominate the strong interaction in hadron phase, it was rather difficult to understand how the in-medium properties of the massive ρ meson could be consistent with the restoration of local isospin symmetry. On the other hand, within the microscopic theory for the strong interaction, namely, the QCD which is a color SU(3) gauge theory, the chiral symmetry is approximately conserved. The spontaneous chiral symmetry breaking and its restoration can be manifested in effective QCD models. Based on the latter, Brown and Rho (BR) proposed the in-medium scaling law [12] implying that hadron masses and meson coupling constants in the Welacka model [13] approach zero at the chiral limit. The scaling was treated in the hadronic phase before the chiral symmetry restoration.

As an effective QCD field theory, the hidden local symmetry theory has been developed to include the ρ meson in addition to the pion in the framework of the chiral perturbative theory by Harada and Yamawaki [14,15] and it is shown that the ρ meson becomes massless at the chiral limit. This supports the mass dropping scenario of the BR scaling. There are also experimental indication for the mass dropping, i.e., the dielectron mass spectra observed at the CERN SPS [16,17], the ω meson mass shift measured at the KEK [18] and the ELSA-Bonn [19], as well as the analysis of the STAR data [20,21]. However, data from the NA60 Collaboration for the dimuon spectrum [22] seem to favor the explanation of ρ meson broadening based on a many-body approach [23]. So far, the controversy is still unsettled [21]. The chiral symmetry and its spontaneous breaking are closely related to the mass acquisition and dropping of hadrons. Since the chiral symmetry is a characteristic of the strong interaction within the QCD, it is favorable to include in the RMF models effects of the chiral symmetry through the BR scaling law. However, this does not mean that the contribution of the many-body correlations [24] is excluded. Actually, the contribution of the many-body correlations can be included phenomenologically into the RMF models to reproduce the saturation properties of nuclear matter.

The in-medium ρ meson plays an important role in modifying the density dependence of the symmetry energy. For most RMF models that the ρ meson mass is not modified by the medium, the symmetry energy is almost linear in density. The introduction of the isoscalar–isovector coupling in RMF models can soften the symmetry energy at high densities [3]. Meanwhile, it reproduces the neutron-skin thickness in ^{208}Pb as that given by the non-relativistic models (about 0.22 fm) [25], consistent with the available data [26]. In well-fitted RMF models that give a value of incompressibility $\kappa = 230$ MeV, a large coefficient of non-linear self-interacting ω meson term is required [25] and thus the naturalness breaks down. Moreover, the isoscalar–isovector coupling in the RMF models increases the effective ρ meson mass with density, which leads the model to be far away from the chiral limit.

The Walecka model with the density-dependent parameters is the simplest version to incorporate the effects of chiral symmetry. The Lagrangian is written as

$$\begin{aligned}\mathcal{L} = {} & \bar{\psi}\big[i\gamma_\mu\partial^\mu - M^* + g_\sigma^*\sigma - g_\omega^*\gamma_\mu\omega^\mu - g_\rho^*\gamma_\mu\tau_3 b_0^\mu\big]\psi \\ & + \frac{1}{2}\big(\partial_\mu\sigma\partial^\mu\sigma - m_\sigma^{*2}\sigma^2\big) - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^{*2}\omega_\mu\omega^\mu \\ & - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \frac{1}{2}m_\rho^{*2}b_{0\mu}b_0^\mu, \end{aligned} \tag{1}$$

where ψ, σ, ω, and b_0 are the fields of the nucleon, scalar, vector, and isovector–vector mesons, with their in-medium scaled masses M^*, m_σ^*, m_ω^*, and m_ρ^*, respectively. The meson coupling constants and hadron masses with asterisks denote the density dependence, given by the BR scaling. The energy density and pressure read, respectively,

$$\begin{aligned}\mathcal{E} = {} & \frac{1}{2}C_\omega^2\rho^2 + \frac{1}{2}C_\rho^2\rho^2\delta^2 + \frac{1}{2}\tilde{C}_\sigma^2\big(m_N^* - M^*\big)^2 \\ & + \sum_{i=p,n}\frac{2}{(2\pi)^3}\int_0^{k_{Fi}} d^3k E^*, \end{aligned} \tag{2}$$

$$\begin{aligned}p = {} & \frac{1}{2}C_\omega^2\rho^2 + \frac{1}{2}C_\rho^2\rho^2\delta^2 - \frac{1}{2}\tilde{C}_\sigma^2\big(m_N^* - M^*\big)^2 \\ & - \Sigma_0\rho + \frac{1}{3}\sum_{i=p,n}\frac{2}{(2\pi)^3}\int_0^{k_{Fi}} d^3k\frac{\mathbf{k}^2}{E^*}, \end{aligned} \tag{3}$$

where $C_\omega = g_\omega^*/m_\omega^*$, $C_\rho = g_\rho^*/m_\rho^*$, $\tilde{C}_\sigma = m_\sigma^*/g_\sigma^*$, $E^* = \sqrt{\mathbf{k}^2 + m_N^{*\,2}}$ with $m_N^* = M^* - g_\sigma^*\sigma$ the effective mass of nucleon, and k_F is the Fermi momentum. The incompressibility of symmetric matter can be expressed explicitly as [27]

$$\kappa = 9\rho\frac{\partial\mu}{\partial\rho} = 9\rho\left(C_\omega^2 + 2C_\omega\rho\frac{\partial C_\omega}{\partial\rho} + \frac{\partial E_F}{\partial\rho} - \frac{\partial\Sigma_0}{\partial\rho}\right), \tag{4}$$

where the chemical potential is given by $\mu = \partial\mathcal{E}/\partial\rho$ and the Fermi energy is $E_F = \sqrt{k_F^2 + m_N^{*\,2}}$. The rearrangement term is

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