Massive neutron stars with small radii in relativistic mean-field models optimized to nuclear ground states

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ABSTRACT

We present an equation of state (EoS) for neutron stars using the relativistic mean-field model with isoscalar- and isovector-meson mixing. Taking into account the results of the neutron skin thickness, $R_{\text{skin}}$, of $^{208}\text{Pb}$ reported by the PREX collaboration, the dimensionless tidal deformability of a canonical neutron star observed from GW170817, and a $2.6\ M_\odot$ compact star implied by the secondary component of GW190814, a new effective interaction is constructed so as to reproduce the saturation condition of nuclear matter and the ground-state properties of finite, closed-shell nuclei. We find that the neutron star EoS exhibits the rapid stiffening around twice the nuclear saturation density, which is caused by the soft nuclear symmetry energy, $E_{\text{sym}}$. It is also noticeable that the thick $R_{\text{skin}}$ from the PREX-2 experiment can be achieved with the small slope parameter of $E_{\text{sym}}$ stemming from the isoscalar-meson mixing. Thus, we speculate that the secondary component of GW190814 is the heaviest neutron star ever discovered.

Keywords: Gravitational waves (678); Neutron stars (1108); Nuclear astrophysics (1129); Relativistic mechanics (1391); Nuclear physics (2077)

1. INTRODUCTION

The astrophysical phenomena concerning compact stars as well as the properties of finite nuclei and nuclear matter are determined by the nuclear equation of state (EoS), characterized by the relation between the energy density and pressure of the system. Owing to the precise observations of neutron stars, such as the Shapiro delay measurement of a binary millisecond pulsar J1614$-$2230 (Demorest et al. 2010; Arzoumanian et al. 2018) and the radius measurement of PSR J0740+6620 from Neutron Star Interior Composition Explorer (NICER) and from X-ray Multi-Mirror (XMM-Newton) Data (Miller et al. 2021), theoretical studies have been currently performed more than ever to elucidate neutron star physics through the EoS for dense matter.

In addition, the direct detection of gravitational-wave (GW) signals from a binary neutron star merger, GW170817, observed by Advanced LIGO and Advanced Virgo detectors, have placed stringent restrictions on the mass–radius relation of neutron stars (Abbott et al. 2017, 2018, 2019). Especially, the tidal deformability of a neutron star (Hinderer 2008; Hinderer et al. 2010) plays an important role in constructing the EoS for neutron star matter (Annala et al. 2018; Lim & Holt 2018; Raithel et al. 2018). Moreover, the secondary component of GW190814 with the mass of $2.6\ M_\odot$ poses another fascinating question whether it is the lightest black hole or the heaviest neutron star (Abbott et al. 2020). Recently, several ideas on this new topic have been proposed in astrophysics. Fattoyev et al. (2020) have insisted that the $2.6\ M_\odot$ object is likely to be the lightest black hole ever discovered using the nucleonic EoS. In contrast, others support the possibility of the secondary object of GW190814 as a neutron star (Huang et al. 2020; Biswas et al. 2021; Bombaci et al. 2021; Dexheimer et al. 2021; Drischler et al. 2021; Ferreira & Providência 2021; Lim et al. 2021; Lopes & Menezes 2022; Miao et al. 2021; Wu et al. 2021; Wang et al. 2022).

On the other hand, a critical issue has been raised in nuclear physics since the accurate determination of neutron skin thickness, $R_{\text{skin}}$, of $^{208}\text{Pb}$ through parity-
The recently updated Lagrangian density in RMF approximation is employed to construct the EoS for nuclear and neutron star matter (Miyatsu et al. 2022). We introduce the isoscalar (σ and ω) and isovector (δ and ρ) mesons as well as nucleons (N = p, n). The interacting Lagrangian density is then given by

\[ L_{\text{int}} = \sum_N \bar{\psi}_N \left[ g_\sigma \sigma - g_\omega \gamma_\mu \omega^\mu + g_\delta \delta \cdot \tau_N \right] \psi_N - U_{\text{NL}}(\sigma, \omega^\mu, \delta, \rho^\mu), \]

where ψN is the nucleon field and \( \tau_N \) is its isospin matrix. The meson-nucleon coupling constants are respectively denoted by \( g_\sigma, g_\omega, g_\delta, \) and \( g_\rho. \) A nonlinear potential is here supplemented as

\[ U_{\text{NL}}(\sigma, \omega^\mu, \delta, \rho^\mu) = \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 - \frac{1}{4} c_3 (\omega^\mu \omega^\mu)^2 - \frac{1}{4} \Lambda_\omega (\rho^\mu \cdot \rho^\mu)^2 \]

with five coupling constants and mixing parameters, \( g_2, g_3, c_3, \Lambda_\omega, \) and \( \Lambda_\rho. \) For describing the characteristics of finite nuclei, the Coulomb interaction, \( \mathcal{L}_C = -e \bar{\psi}_\nu \gamma_\mu A^\mu \psi_\nu, \) for photon \( A^\mu \) is also taken into consideration.

### 3. RESULTS AND DISCUSSIONS

A new effective interaction can reproduce the saturation properties of nuclear matter and the characteristics of finite nuclei. The resulting parameter set—henceforth referred to as the OMEG (Origin of Matter and Evolution of Galaxies) interaction—is listed in Table 1. There are three modifications from the previous work (Miyatsu et al. 2022). We change \( \rho_0 \) into 0.15 fm\(^{-3}\) in order to describe the weak charge and baryon density profiles of \( ^{208}\text{Pb} \) as well as its experimental charge density profile, based on the PREX-2 result (Horowitz et al. 2020; Adhikari et al. 2021). In addition, because of the strong correlation between \( \Lambda_{1,4} \) and \( M^*_N \) (Hornick et al. 2018; Choi et al. 2021), the effective mass ratio of nucleon at \( \rho_0 \) is fixed by \( M^*_N/M_N = 0.64 \) to accomplish the observed \( \Lambda_{1,4} \) from GW170817, which is within the mass range in Li et al. (2018). Furthermore, the \( \delta-N \) coupling constant is tuned so as to enhance the \( \delta \)-meson effect on the isospin-asymmetric nuclear EoS. In the present study,
Table 1. Model parameters and properties of nuclear matter at $\rho_0$.

| Model parameters | Bulk properties |
|------------------|-----------------|
| $g_\sigma$ | $\rho_0$ (fm$^{-3}$) | 0.15 |
| $g_\omega$ | $M_N/M_N$ | 0.64 |
| $g_\rho$ | $E_0$ (MeV) | -16.45 |
| $g_\omega$ (fm$^{-1}$) | $J_0$ (MeV) | -66.98 |
| $g_3$ | $E_{sym}$ (MeV) | 34.55 |
| $c_3$ | $L$ (MeV) | 50.00 |
| $\Lambda_{\sigma\delta}$ | $K_{sym}$ (MeV) | -384.43 |
| $\Lambda_{\sigma\rho}$ | $J_{sym}$ (MeV) | -533.43 |

Note—The nucleon and meson masses are respectively fixed by $M_N = 939.00$ MeV, $m_\sigma = 496.50$ MeV, $m_\omega = 782.66$ MeV, $m_\rho = 980.00$ MeV, and $m_\omega = 775.26$ MeV (Zyla et al. 2020). The bulk properties of nuclear matter are given by the coefficients based on the expansion of isospin-asymmetric nuclear EoS with power series in the isospin asymmetry around $\rho_0$ (Stone et al. 2014; Choi et al. 2021).

Table 2. Theoretical predictions for ground-state properties of several closed-shell nuclei.

| Nucleus | $B/A$ (MeV) | $R_{sym}$ (fm) | $R_{skin}$ (fm) |
|---------|-------------|---------------|-----------------|
| $^{16}\text{O}$ | Theory | 8.03 | 2.75 | 2.70 | -0.03 |
|   | Exp. | 7.98 | 3.48 | 3.48 | -0.05 |
| $^{40}\text{Ca}$ | Theory | 8.58 | 3.50 | 3.50 | 0.20 |
|   | Exp. | 8.55 | 3.50 | 3.48 | 0.20 |
| $^{48}\text{Ca}$ | Theory | 8.68 | 3.89 | 3.89 | 0.22 |
|   | Exp. | 8.68 | 3.89 | 3.89 | 0.22 |
| $^{90}\text{Zr}$ | Theory | 8.71 | 4.28 | 4.27 | 0.09 |
|   | Exp. | 8.71 | 4.28 | 4.27 | 0.09 |
| $^{100}\text{Sn}$ | Theory | 8.25 | 4.49 | 4.49 | -0.08 |
|   | Exp. | 8.25 | 4.49 | 4.49 | -0.08 |
| $^{132}\text{Sn}$ | Theory | 8.34 | 4.72 | 4.71 | 0.29 |
|   | Exp. | 8.35 | 4.72 | 4.71 | 0.29 |
| $^{208}\text{Pb}$ | Theory | 7.90 | 5.51 | 5.50 | 0.23 |
|   | Exp. | 7.87 | 5.51 | 5.50 | 0.23 |

Note—Experimental data for the binding energy per nucleon, $B/A$, and charge radius, $R_{ch}$, are referred to Wang et al. (2021) and Angeli & Marinova (2013), respectively.

Figure 1. Nuclear symmetry energy, $E_{sym}$, as a function of the baryon density ratio, $\rho_B/\rho_0$. The constraints from analyses of heavy-ion collision data using the isospin-dependent Boltzmann–Uehling–Uhlenbeck (IBUU04) and improved quantum molecular dynamics (ImQMD) transport models are presented (Chen et al. 2005a; Li & Chen 2005; Tsang et al. 2009). We also show the constraints on the magnitude of $E_{sym}$ at $2\rho_0$: $E_{sym}(2\rho_0) \approx 40.2 \pm 12.8$ MeV based on microscopic calculations with various energy density functionals (Chen 2015), and $E_{sym}(2\rho_0) \approx 51 \pm 13$ MeV from nine new analyses of neutron star observables since GW170817 (Li et al. 2021).

and its mixing enable us to obtain relatively thick $R_{skin}$ even in the calculations with small $L$. We here find that the OMEG interaction provides $R_{skin} = 0.23$ fm with $L = 50$ MeV, which satisfies the PREX-2 data of $0.283 \pm 0.071$ fm (Adhikari et al. 2021).

The density dependence of nuclear symmetry energy, $E_{sym}$, for the OMEG interaction is displayed in Figure 1. Various theoretical calculations using the well-calibrated parameter sets based on the RMF models are also presented: BigApple (Fattoyev et al. 2020), FSUGarnet (Chen & Piekarewicz 2015), FSUGold (Fattoyev & Piekarewicz 2010), FSUGold2 (Chen & Piekarewicz 2014), IOPB-I (Kumar et al. 2018), IU-FSU (Fattoyev et al. 2010), NL3 (Lalazissis et al. 1997), PD15 (Liliani et al. 2021), TAMUC-FSUa (Fattoyev & Piekarewicz 2013; Piekarewicz 2014), and TM1 (Sugahara & Toki 1994).

As explained in the previous study (Miyatsu et al. 2022), $E_{sym}$ for the OMEG interaction shows an inflection point above $\rho_0$, the rapid reduction around $1.5\rho_0 - 2.8\rho_0$, and the suppression above $3\rho_0$, which are caused by the strong $\sigma-\delta$ mixing. This behavior is similar to the cusp in $E_{sym}$ using the skyrmion crystal approach (Ma & Rho 2021; Lee et al. 2022) and to the results in the Skyrme Hartree-Fock calculations (Chen et al. 2005b).

The density dependence of pressure, $P$, is depicted in Figure 2. The EoS for the OMEG interaction is rather stiff in symmetric nuclear matter, similar to those for

we set $g_\sigma^2/4\pi = 3$, at which the curvature parameter of nuclear symmetry energy, $K_{sym}$, attains a minimum limit (Miyatsu et al. 2022). Note that the $\sigma-\delta$ mixing parameter, $\Lambda_{\sigma\delta} = 87$, is adopted to ensure the matter stability of charge fluctuations. When $\Lambda_{\sigma\delta}$ is larger than the current value, then nuclear matter becomes unstable at high densities and the phase transition should be considered (Kubis et al. 2020).

The binding energies and charge radii of several closed-shell nuclei for the OMEG interaction are summarized in Table 2. Although the small value of $L$ generally gives thin $R_{skin}$ in the RMF models, the $\delta$ meson

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It is found that only the Bi-form matter in the crust region, where nuclei are taken presented in Figure 3. We here employ the EoS for nonuniform matter, the OMEG interaction shows a slow growth above $\rho_0$ and then a sharp increase around $2\rho_0$. At high densities, it almost satisfies the constraint from elliptical flow data (Danielewicz et al. 2002). Here, we can verify that the phase transition due to the matter instability does not occur even at high densities because the condition of $dP/d\rho_B > 0$ is ensured in pure neutron matter.

Since the discovery of PSR J1614–2230 with the mass of $1.908 \pm 0.016 M_\odot$ (Demorest et al. 2010; Arzounian et al. 2018), the EoS for neutron stars has been constructed so as to support $2 M_\odot$. However, PSR J0952–0607, which has the largest well-measured mass of $2.35 \pm 0.17 M_\odot$ with small modeling uncertainties, has been reported very recently (Romani et al. 2022). Furthermore, we have no reason to ignore the possibility of the secondary object of GW190814 as a neutron star (Abbott et al. 2020). Therefore, at present, the maximum mass of a neutron star, $M_{\text{max}}$, namely the Tolman–Oppenheimer–Volkoff (TOV) limit, might be larger than ever.

The mass–radius relations of neutron stars are presented in Figure 3. We here employ the EoS for nonuniform matter in the crust region, where nuclei are taken into account using the Thomas–Fermi calculation (Miyatsu et al. 2013b, 2015). It is found that only the BigApple and OMEG interactions account for both constraints: $M_{\text{max}} \geq 2.35 M_\odot$ and the neutron star radii from J0030+0451 by a NICER view (1.44$^{+0.15}_{-0.14}$ $M_\odot$ and 13.02$^{+1.24}_{-1.14}$ km (Miller et al. 2019) and 1.34$^{+0.15}_{-0.16}$ $M_\odot$ and 12.71$^{+1.19}_{-1.17}$ km (Riley et al. 2019)), PSR J0348+0431 (2.01 $\pm$ 0.04 $M_\odot$) (Antoniadis et al. 2013), PSR J0740+6620 (2.07$^{+0.067}_{-0.056}$ $M_\odot$ and 12.39$^{+1.30}_{-0.98}$ km) (Cromartie et al. 2019; Fonseca et al. 2021; Riley et al. 2021), and the secondary object of GW190814 (2.59$^{+0.09}_{-0.08}$ $M_\odot$) (Abbott et al. 2020).

We notice that the nonlinear $\omega$ self-coupling in Equation (2) seems to be no longer necessary for supporting a hypermassive neutron star because its coupling constant, $c_3$, is very small and zero for the BigApple and OMEG interactions, respectively. Moreover, the two interactions have a unique feature of $R_{2,0} > R_{1.4}$, where $R_{2,0(1.4)}$ is the neutron star radius with the mass of $2.0(1.4)$ $M_\odot$, as mentioned in Drischler et al. (2022). Furthermore, the OMEG interaction is consistent with the theoretical restriction using Bayesian inference based on the combined data from astrophysical multi-messenger observations of neutron stars and from heavy-ion collisions of gold nuclei at relativistic energies with microscopic calculations (Huth et al. 2022).

In Figure 4, the speed of sound, $c_s = \sqrt{\frac{dP}{d\epsilon}}$, in neutron star matter is illustrated as a function of $\rho_B/\rho_0$. Because any exotic degrees of freedom in the core of a neutron star are not included, $c_s$ reaches a plateau at high densities. At the central density of $M_{\text{max}}$, the BigApple, NL3, and OMEG interactions exceed $c_s \simeq 0.85$, while the others lie around the conformal limit (Alford et al. 2013). It is thus found that $c_s$ is much larger than...
the conformal limit in the core of a hypermassive neutron star. For the OMEG interaction, the rapid growth of $c_s$ occurs around $2\rho_0$, where the EoS for pure neutron matter changes considerably due to the $\delta$ meson and its mixing, as already explained in Figure 2. Note the similar growth of $c_s$ is also seen in QCIC21 based on the framework of quark–hadron crossover (Kojo et al. 2022).

In the upper panel of Figure 5, we present the correlation between $\Lambda_{1.4}$ and $R_{1.4}$. As explained in Nandi et al. (2019), $\Lambda_{1.4}$ strongly interrelates with $R_{1.4}$. In addition, $\Lambda_{1.4}$ is roughly associated with $L$ via $R_{1.4}$. We find that the observed $\Lambda_{1.4}$ from GW170817 favors the small $R_{1.4}$ and hence $L$ too. If both restrictions on $\Lambda_{1.4}$ from GW170817 and GW190814 are taken into account, only the IF-FSU, PD15, and OMEG interactions are acceptable as the appropriate EoS for neutron stars. It is thus possible to mention that $R_{1.4}$ lies around 12.5 km and $L$ is in the range of $40 \leq L(\text{MeV}) \leq 50$.

The lower panel of Figure 5 shows the correlation between $R_{\text{skin}}$ and $R_{1.4}$. In general, the larger $R_{1.4}$ provides the thicker $R_{\text{skin}}$ of $^{208}\text{Pb}$ in the usual RMF models. To describe the PREX-2 result, $L$ is thus larger than 64 MeV, given by the IOPB-I interaction. Meanwhile, only the OMEG interaction can support the PREX-2 data with the small $L$ (= 50 MeV) due to the $\sigma$–$\delta$ mixing. In addition, it almost fulfills the experimental result of $R_{\text{skin}}$, implied by the determination of electric dipole strength distribution in $^{48}\text{Ca}$ at RCNP (Birkhan et al. 2017). However, it is difficult to explain the latest data reported by the CREX collaboration (Adhikari et al. 2022). From this fact, we may infer that the results of the PREX-2 and CREX experiments seem to be incompatible in the present calculations.

4. SUMMARY AND CONCLUSION

Using the RMF model with the isoscalar- and isovector-meson mixing, $\sigma^2\delta^2$ and $\omega_\mu\omega^\nu p_\mu p^\nu$, we have presented an EoS for nuclear and neutron star matter, which can explain both data from terrestrial experiments and astrophysical observations of neutron stars. A new effective interaction, dubbed the OMEG interaction, has been constructed so as to reproduce the saturation condition of nuclear matter and the ground-state properties of finite nuclei. In particular, we have then focused on the recent experimental and observational results: the $R_{\text{skin}}$ of $^{208}\text{Pb}$ reported by the PREX collaboration (Adhikari et al. 2021), the $\Lambda_{1.4}$ observed from GW170817 (Abbott et al. 2018), and a 2.6 $M_\odot$ compact
star implied by the secondary object of GW190814 (Abbott et al. 2020).

We have demonstrated that the OMEG interaction successfully accounts for the binding energies and charge radii of several closed-shell nuclei. Especially, the thick $R_{\text{skin}}$ measured by the PREX-2 experiment is achieved with small $L$ using the $\sigma-\delta$ mixing. Compared with the well-calibrated RMF models, $E_{\text{sym}}$ becomes very soft at high densities because the $\sigma-\delta$ mixing strongly affects its density dependence. Furthermore, the neutron star EoS for the OMEG interaction is soft up to $1.5\rho_0$, and exhibits the rapid stiffening around $2\rho_0$. It is then found that $M_{\text{max}}$ exceeds the recently observed massive neutron star, PSR J0952−0607, which has the largest well-measured mass of $2.35 \pm 0.17 \, M_\odot$ with small modeling uncertainties (Romani et al. 2022). Moreover, it is possible for the OMEG interaction to satisfy the constraints on $\Lambda_{14}$ observed from GW170817 and GW190814. Finally, we have thus speculated that the secondary component of GW190814 with the mass of $2.6 \, M_\odot$ is the heaviest neutron star ever discovered.

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