Effects of a weakly interacting light U boson on the nuclear equation of state and properties of neutron stars in relativistic models

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We investigate the effects of the light vector U-boson that couples weakly to nucleons in relativistic mean-field models on the equation of state and subsequently the consequence in neutron stars. It is analyzed that the U-boson can lead to a much clearer rise of the neutron star maximum mass in models with the much softer equation of state. The inclusion of the U-boson may thus allow the existence of the non-nucleonic degrees of freedom in the interior of large mass neutron stars initiated with the favorably soft EOS of normal nuclear matter. In addition, the sensitive role of the U-boson in the neutron star radius and its relation to the test of the non-Newtonian gravity that is herein addressed by the light U-boson are discussed.

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I. INTRODUCTION

Confronting nuclear physics, we should highlight the great importance of the equation of state (EOS), for it being significantly important to study the structure of nuclei, the reaction dynamics of heavy-ion collisions, and many issues in astrophysics [1–4]. The nuclear EOS consists usually of two ingredients: the energy density for symmetric matter and the density dependence of the symmetry energy. For the former, the saturation properties are quite clear nowadays, though its high-density behavior remains to be revealed in more details. However, the density dependence of the symmetry energy is still poorly known especially at high densities [4–7], and even the trend of the density dependence of the symmetry energy can be predicted to be contrary. While most relativistic theories [2, 3, 8–12] and some non-relativistic theories [5, 7, 13, 14] predict that the symmetry energy increases continuously at all densities, many other non-relativistic theories (for instance, see [5, 13, 15, 16]), in contrast, predict that the symmetry energy first increases, then decreases above certain supra-saturation densities, and even in some predictions [4–6] becomes negative at high densities, referred as the super-soft symmetry energy. Therefore, the experimental extraction is of necessity.

Recently, by analyzing the FOPI/GSI data on the π^-/π^+ radio in relativistic heavy-ion collisions [17], the evidence for a super-soft symmetry energy was found [18]. This finding can result in many consequences, while a direct challenge is how to stabilize a normal neutron star with the

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super-soft symmetry energy. Conventionally, a mechanical instability may occur if the symmetry energy starts decreasing quickly above the certain supra-saturation density [15, 19, 20]. To solve this problem, one possible way is to take into account the hadron-quark phase transition which lifts up the pressure in pure quark matter [21], while the transition is expected to occur at much higher densities within a narrow region of parameters. Instead, one may consider the possible correction to the gravity. Though the gravitational force was first discovered in the history, it is still the most poorly characterized, compared to three other fundamental forces that can be favorably unified within the gauge theory. For the further grand unification of four forces, the correction to the conventional gravity seems necessary. The light U-boson, which is proposed beyond the standard model, can play the role in deviating from the inverse square law of the gravity due to the Yukawa-type coupling, see Refs. [20, 22–24] and references therein. This light U-boson was used as the interaction propagator of the MeV dark matter and was used to account for the bright 511 keV γ-ray from the galactic bulge [25–30]. As a consequence of its weak coupling to baryons, the stable neutron star can be obtained in the presence of the super-soft symmetry energy [20]. In addition, it is noted that through the reanalysis of the FOPI/GSI data with a different dynamical model another group extracted a contrary density dependent trend of the symmetry energy at high densities [31]. The solution of the controversy is still in progress.

In pursuit of the covariance in addressing neutron stars bound by the strong gravity, the relativistic models are favorable to obtain the EOS, though the fraction, arisen from the relativistic effect of fast particles in the compact core of neutron stars, is just moderate. Apart from the non-relativistic models to obtain the EOS of neutron stars in Ref. [20], we will adopt the relativistic mean-field (RMF) models in this work. The RMF theory which is based on the Dirac equations for nucleons with the potentials given by the meson exchanges achieved great success in the past few decades [32–41]. The original Lagrangian of the RMF model was first proposed by Walecka more than 30 years ago [32]. The Walecka model and its improved versions were characteristic of the cancellation between the big attractive scalar field and the big repulsive vector field. To soften the EOS obtained with the simple Walecka model, the proper medium effects were accounted with the inclusion of the nonlinear self-interactions of the σ meson proposed by Boguta et. al. [33]. A few successful nonlinear RMF models, such as NL1 [42], NL2 [43], NL-SH [44], NL3 [45], and etc., had been obtained by fitting saturation properties and ground-state properties of a few spherical nuclei. Later on, an extension to include the self-interaction of ω meson was implemented to obtain RMF potentials which were required to be consistent with the Dirac-Brueckner self-energies [46]. In this direction, besides the early model TM1 [46], there were recent versions PK1 [47] and FSUGold [48].

Although various RMF models reproduce successfully the saturation properties of nuclear matter

and structural properties of finite nuclei, the corresponding EOS's may behave quite differently at high densities especially in isospin-asymmetric nuclear matter. It was reported in the literature [20, 23] that the light U-boson can significantly modify the EOS in isospin-asymmetric matter. However, the further systematic work to analyze the effect of the light U-boson on various nuclear EOS's is still absent. In this work, we will investigate in detail the effect of light U-boson on the EOS and properties of neutron stars with various RMF models. In particular, we will address the difference of the effects induced by the U-boson in various RMF models.

The paper is organized as follows. In Sec. II, we present briefly the formalism based on the Lagrangian of the relativistic mean-field models. In Sec. III, numerical results and discussions are presented. At last, a summary is given in Sec. IV.

II. FORMALISM

In the RMF approach, the nucleon-nucleon interaction is usually described via the exchange of three mesons: the isoscalar meson σ, which provides the medium-range attraction between the nucleons, the isoscalar-vector meson ω, which offers the short-range repulsion, and the isovector-vector meson b_0, which accounts for the isospin dependence of the nuclear force. The relativistic Lagrangian can be written as:

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

where $\psi, \sigma, \omega, b_0$ are the fields of the nucleon, scalar, vector, and neutral isovector-vector mesons, with their masses M, m_σ, m_ω, and m_ρ, respectively. $g_i(i = \sigma, \omega, \rho)$ are the corresponding meson-nucleon couplings. $F_{\mu\nu}$ and $B_{\mu\nu}$ are the strength tensors of ω and ρ mesons respectively,

$$
F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu, \ B_{\mu\nu} = \partial_\mu b_{0\nu} - \partial_\nu b_{0\mu}.
\tag{2}
$$

The self-interacting terms of σ, ω mesons and the isoscalar-isovector coupling are given generally as

$$
\begin{aligned}
U_{\text{eff}}(\sigma, \omega^\mu, b_0^\mu) &= -\frac{1}{3}g_2\sigma^3 - \frac{1}{4}g_3\sigma^4 + \frac{1}{4}c_3(\omega_\mu\omega^\mu)^2 \\
&\quad +4\Lambda_V g_\rho^2 g_\omega^2 \omega_\mu\omega^\mu b_{0\mu}b_0^\mu.
\end{aligned}
\tag{3}
$$

Here, the isoscalar-isovector coupling term is introduced to modify the density dependence of the symmetry energy [2]. In addition, we include in Lagrangian $\mathcal{L}_u$ for the U-boson that is beyond the standard model. A very light U-boson can be utilized to interpret the deviation from the Newton's

gravitational potential which is usually characterized in the form [20, 23]:

$$V(r) = -\frac{G_\infty m_1 m_2}{r}(1 + \alpha e^{-r/\lambda}) \tag{4}$$

where G_∞ is the universal gravitational constant, $\alpha = -g_u^2/4\pi G_\infty M_B^2$ is a dimensionless strength parameter with g_u and M_B being the boson-nucleon coupling constant and baryon mass, respectively, and $\lambda = 1/m_u$ is the length scale with m_u being the boson mass. According to the conventional view, the Yukawa-type correction to the Newtonian gravity resides at the matter part rather than the geometric part. Thus, following the form of the vector meson, $\mathcal{L}_u$ is written as:

$$\mathcal{L}_u = -\overline{\psi}g_u\gamma_\mu u^\mu \psi - \frac{1}{4}U_{\mu\nu}U^{\mu\nu} + \frac{1}{2}m_u^2 u_\mu u^\mu, \tag{5}$$

with u the field of U-boson. $U_{\mu\nu}$ is the strength tensor of U-boson,

$$U_{\mu\nu} = \partial_\mu u_\nu - \partial_\nu u_\mu. \tag{6}$$

With the standard Euler-Lagrange formala, we can deduce from the Lagrangian the equations of motion for the nucleon and mesons. They are given as follows:

$$[i\gamma_\mu\partial^\mu - M + g_\sigma\sigma - g_\omega\gamma_\mu\omega^\mu - g_u\gamma_\mu u^\mu - g_\rho\gamma_\mu\tau_3 b_0^\mu]\psi = 0 \tag{7}$$

$$(\partial_t^2 - \nabla^2 + m_\sigma^2)\sigma = g_\sigma\overline{\psi}\psi - g_2\sigma^2 - g_3\sigma^3, \tag{8}$$

$$(\partial_t^2 - \nabla^2 + m_\omega^2)\omega_\mu = g_\omega\overline{\psi}\gamma_\mu\psi - c_3\omega_\mu^3 - 8\Lambda_V g_\rho^2 g_\omega^2 b_{0\mu} b_0^\mu \omega_\mu, \tag{9}$$

$$(\partial_t^2 - \nabla^2 + m_\rho^2)b_{0\mu} = g_\rho\overline{\psi}\gamma_\mu\tau_3\psi - 8\Lambda_V g_\rho^2 g_\omega^2 \omega_\mu\omega^\mu b_{0\mu}, \tag{10}$$

$$(\partial_t^2 - \nabla^2 + m_u^2)u_\mu = g_u\overline{\psi}\gamma_\mu\psi. \tag{11}$$

In the mean-field approximation, all derivative terms drop out and the expectation values of space-like components of vector fields vanish (only zero components survive) due to translational invariance and rotational symmetry of the nuclear matter. In addition, only the third component of isovector fields survives because of the charge conservation. In the mean-field approximation, after the Dirac field of nucleons is quantized [35], the fields of mesons and U-boson, which are replaced by their classical expectation values, obey following equations:

$$m_\sigma^2\sigma = g_\sigma\rho_s - g_2\sigma^2 - g_3\sigma^3, \tag{12}$$

$$m_\omega^2\omega_0 = g_\omega\rho_B - c_3\omega_0^3 - 8\Lambda_V g_\rho^2 g_\omega^2 b_0^2 \omega_0, \tag{13}$$

$$m_\rho^2 b_0 = g_\rho\rho_3 - 8\Lambda_V g_\rho^2 g_\omega^2 \omega_0^2 b_0, \tag{14}$$

$$m_u^2 u_0 = g_u\rho_B, \tag{15}$$

where ρ_s and ρ_B are the scalar and baryon densities, respectively, and ρ_3 is the difference between the proton and neutron densities, namely, $\rho_3 = \rho_p - \rho_n$. The set of coupled equations can be solved

self-consistently using the iteration method. With these mean-field quantities, the resulting energy density ε and pressure P are written as:

$$\varepsilon = \sum_{i=p,n} \frac{2}{(2\pi)^3} \int^{k_{F_i}} d^3k E_i^* + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} \frac{g_u^2}{m_u^2} \rho_B^2 + \frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{1}{2} m_\rho^2 b_0^2$$

$$+ \frac{1}{3} g_2 \sigma^3 + \frac{1}{4} g_3 \sigma^4 + \frac{3}{4} c_3 \omega_0^4 + 12 \Lambda_V g_\rho^2 g_\omega^2 \omega_0^2 b_0^2. \tag{16}$$

$$P = \frac{1}{3} \sum_{i=p,n} \frac{2}{(2\pi)^3} \int^{k_{F_i}} d^3k \frac{\mathbf{k}^2}{E_i^*} + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} \frac{g_u^2}{m_u^2} \rho_B^2 - \frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{1}{2} m_\rho^2 b_0^2$$

$$- \frac{1}{3} g_2 \sigma^3 - \frac{1}{4} g_3 \sigma^4 + \frac{1}{4} c_3 \omega_0^4 + 4 \Lambda_V g_\rho^2 g_\omega^2 \omega_0^2 b_0^2, \tag{17}$$

with $E_i^* = \sqrt{\mathbf{k}^2 + (M_i^*)^2}$.

Given above is the formalism for nuclear matter without considering the β equilibrium. For asymmetric nuclear matter at β equilibrium, the chemical equilibrium and charge neutrality conditions need to be additionally considered, which are written as:

$$\mu_n = \mu_p + \mu_e, \tag{18}$$

$$\rho_e = \rho_p, \tag{19}$$

$$\rho_B = \rho_n + \rho_p, \tag{20}$$

where μ_n, μ_p, μ_e are the chemical potential of neutron, proton and electron, respectively, and ρ_e is the number density of electrons. In neutron star matter, the EOS is obtained by adding in Eqs.(16) and (17) the contribution of the free electron gas.

The neutron star properties are obtained from solving the Tolman-Oppenheimer-Volkoff (TOV) equation [49, 50]:

$$\frac{dP(r)}{dr} = -\frac{[P(r) + \varepsilon(r)][M(r) + 4\pi r^3 P(r)]}{r(r - 2M(r))}, \tag{21}$$

$$M(r) = 4\pi \int_0^r d\tilde{r} \tilde{r}^2 \varepsilon(\tilde{r}), \tag{22}$$

where r is the radial coordinate from the center of the star, $p(r)$ and $\varepsilon(r)$ are the pressure and energy density at position r, respectively, and $M(r)$ is the mass contained in the sphere of the radius r. Note that here we use units for which the gravitation constant is $G_\infty = c = 1$. The radius R and mass $M(R)$ of a neutron star are obtained from the condition $p(R) = 0$. Because the neutron star matter, consisting of neutrons, protons, and electrons (npe) at β equilibrium in this work, undergoes a phase transition from the homogeneous matter to the inhomogeneous matter at the low density region, the RMF EOS obtained from the homogeneous matter does not apply to the low density region. For a thorough description of neutron stars, we thus adopt the empirical low-density EOS in the literature [51, 52].

TABLE I: Parameters and saturation properties for various parameter sets. Here, the NL3Λ_V is the same as the original parameter set NL3 but with the readjusted g_ρ after the Λ_V is included to modify the density dependence of the symmetry energy, and the TM1Λ_V to the TM1 is the same as the NL3Λ_V to the NL3. Meson masses, incompressibility and symmetry energy are in units of MeV, and the density is in unit of fm^{-3}.

	g_σ	g_ω	g_ρ	m_σ	m_ω	m_ρ	g_2	g_3	c_3	Λ_V	ρ_0	κ	M^*/M	E_{sym}
NL1	10.138	13.285	4.976	492.250	795.359	763	12.172	-36.265	-	-	0.153	211.3	0.57	43.7
NL-SH	10.444	12.945	4.383	526.059	783.000	763	6.910	-15.834	-	-	0.146	355.4	0.60	36.1
NL3	10.217	12.868	4.474	508.194	782.501	763	10.431	-28.890	-	-	0.148	271.8	0.60	37.4
TM1	10.029	12.614	4.632	511.198	783.000	770	7.233	0.618	71.31	-	0.145	281.2	0.63	36.9
FSUGold	10.592	14.302	5.884	491.500	782.500	763	4.277	49.934	418.39	0.03	0.148	230.0	0.61	32.5
NL3Λ_V	10.217	12.868	5.664	508.194	782.501	763	10.431	-28.890	-	0.03	0.148	271.8	0.60	31.8
TM1Λ_V	10.029	12.614	5.720	511.198	783.000	770	7.233	0.618	71.31	0.03	0.145	281.2	0.63	32.1

III. RESULTS AND DISCUSSIONS

Among a number of nonlinear RMF parametrizations, we select several typical best-fit parameter sets, for instance NL1 [42], NL-SH [44], NL3 [45], TM1 [46] and FSUGold [48], to investigate the effects of the U-boson on the EOS of isospin-asymmetric nuclear matter and properties of neutron stars. The nonlinear RMF models usually include the nonlinear self-interactions of the σ meson to simulate appropriate medium dependence of the strong interaction. This is typical in RMF parameter sets NL1, NL-SH and NL3. In addition to the nonlinear σ meson self-interactions, in TM1 and FSUGold the nonlinear self-interaction of the ω meson is also included. Parameters and saturation properties of these parameter sets are listed in Table I.

In Fig. 1, the energy density and pressure of npe matter at β equilibrium are shown as a function of nucleon density for various models without the inclusion of the U-boson. It is seen that the EOS with parameter sets TM1 and FSUGold is clearly softer than that with the NL1, NL-SH and NL3 with the increase of the density. The softening stems from the inclusion of the nonlinear self-interaction of the ω meson that lowers the repulsion provided by the ω meson at high densities, while the excess softening with the FSUGold as compared to that with the TM1 can be attributed dominately to the larger parameter c_3 in FSUGold.

Shown in Fig. 2 is the correlation between the pressure and the energy density given in Fig. 1. This correlation is usually regarded as the EOS that is used as the input of the Tolman-Oppenheimer-Volkoff (TOV) equation [49, 50] for the evaluation of the neutron star properties. Once again, we see the large deviations in the EOS with different RMF models especially at high densities. In the following, it is thus interesting to see how the U-boson affects the EOS produced by various RMF models that differs largely at high densities.

In the RMF approximation, the contribution of the U-boson in a linear form is just decided by the ratio of the coupling constant to its mass, i.e., g_u/m_u, as seen in Eqs.(16) and (17). In Figs. 3 and 4,
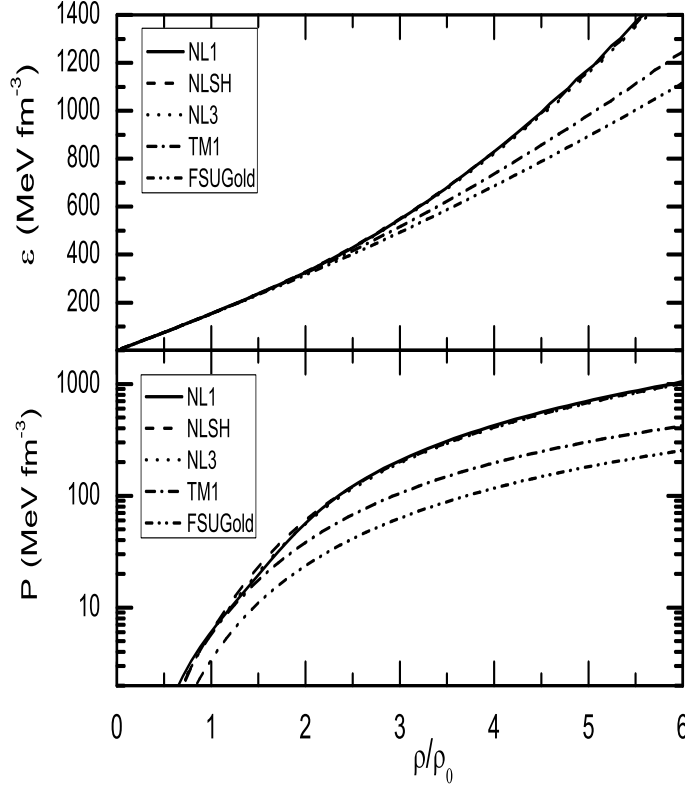
FIG. 1: Energy density ε (upper panel) and pressure P (lower panel) as a function of density with various RMF parameter sets, NL3, NL1, NL-SH, TM1, and FSUGold in npe matter at β equilibrium.

the EOS's with various models are depicted for a set of ratios $(g_u/m_u)^2$. It is shown in Figs. 3 and 4 that the inclusion of the U-boson stiffens the EOS. This is physically obvious since the vector form of the U-boson provides an excess repulsion in addition to the vector mesons, whereas an interestingly large difference appears for different types of models. As shown in Figs. 3 and 4, the EOS's with the TM1 and FSUGold acquires a much more apparent stiffening than that with the NL1, NL-SH and NL3 by including the U-boson. This phenomenon can be understood by the inherent feature of these models. In models NL1, NL-SH and NL3, the repulsion is quadratic in the density because the nonlinear self-interaction of the ω meson is not considered. With the increase of the density, the repulsion provided by the ω meson dominates the attraction provided by the σ meson. The cancellation between the repulsion and attraction in the pressure (see Eq.(17) is not prominent at high densities so that the U-boson plays a similar role in the energy density and pressure. Thus, these EOS's are just moderately modified by the U-boson, as shown in Fig. 3. For models TM1 and FSUGold that feature a clearly softer EOS at high densities, the cancellation between the repulsion and attraction becomes significant and thus sharpens the importance of the U-boson in the pressure. Comparing to the addition of the big repulsion and attraction in the energy density, the U-boson just plays a marginal role in modifying the energy density. Thus, the U-boson can modify appreciably the
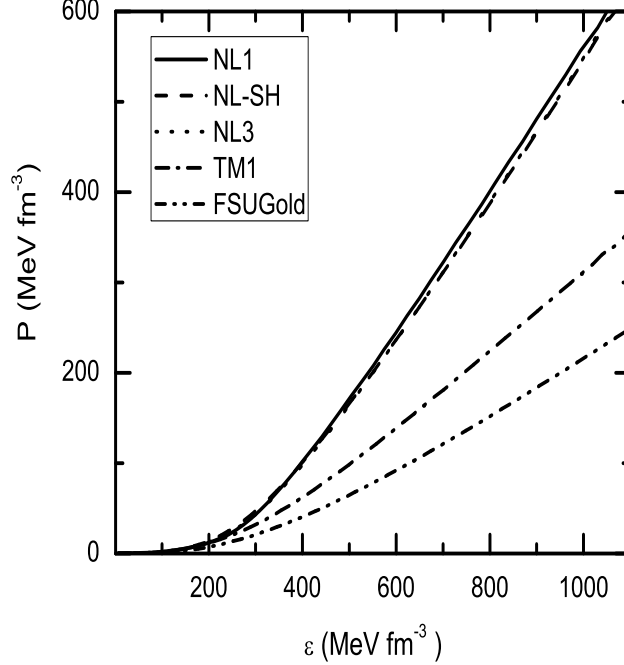
FIG. 2: The correlation between the pressure and the energy density in npe matter at β equilibrium with various RMF models.

correlation between the pressure and energy density in the high-density region in favorably softened models, for instance, the TM1 and FSUGold, as shown in Fig. 4. Because in TM1 and FSUGold the nonlinear term of the ω meson plays a decisive role in softening the EOS, the larger the parameter c_3, the more apparent the modification, as shown comparatively in the upper and lower panels of Fig. 4.

In addition, it is interesting to examine whether the significant difference in the U-boson-induced modification to the EOS can be created by softening the symmetry energy. The symmetry energy is softened by including the isoscalar-isovector coupling term in RMF models (see Eq.(3)). In Fig. 5, we depict the EOS without (upper panels) and with (lower panels) the softening of the symmetry energy in NL3 and TM1. However, no visible difference in two cases with the NL3 is observed, and with the TM1 the difference is not significant. This observation seems to show a contrast with that in Ref. [20] where the fluffy EOS due to the super-soft symmetry energy can be lifted up by the U-boson to support a normal neutron star. In deed, the magnitude of the modification to the EOS caused by the U-boson relies on the softness of the EOS. As long as the EOS is modified significantly by softening the symmetry energy, the stiffening role of the U-boson in the EOS can be considerably enhanced accordingly. Given that the stiff EOS with the NL3 is little modified by softening the symmetry energy, as shown in the inset of the left lower panel in Fig. 5, the softening of the symmetry energy can scarcely affect the role of the U-boson. For models with a softer EOS,
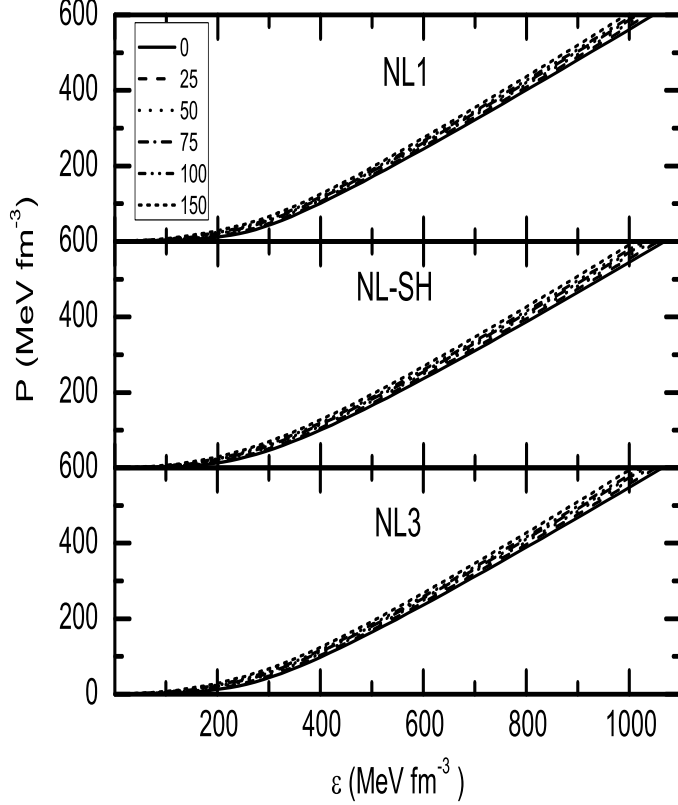
FIG. 3: Equation of state of neutron star matter with three RMF models, NL3, NL1 and NL-SH with the inclusion of the U-boson. The numbers in the legend are the values of $(g_u/m_u)^2$ in units of GeV^{-2}.

the situation can turn out to be different when the EOS is modified appreciably by softening the symmetry energy. Indeed, the vital role of the U-boson in the EOS of the non-relativistic MDI model with a super-soft symmetry energy [20] is a typical case that the role of the U-boson can be largely amplified due to the softening of the symmetry energy. In RMF models, for instance, the TM1 whose EOS is softer than that with the NL3, the softening of the symmetry energy can also result in some visible difference in the EOS and thereby the role of the U-boson, as shown in right panels of Fig. 5.

Next, we turn to the consequences in hydrostatic neutron stars with the EOS modified by the U-boson. Using Eqs.(21) and (22), the mass and radius of hydrostatic neutron stars can be obtained with the given EOS. In Fig. 6, the mass-radius (M-R) relation of neutron stars is depicted with different ratio parameter $(g_u/m_u)^2$ for the U-boson in various models. With the inclusion of the U-boson, we can see that both the maximum mass and radius of neutron stars increase significantly. It is clearly seen that the star maximum mass with the soft EOS is modified more significantly by the U-boson. This is consistent with the corresponding modification to the high-density EOS caused by the U-boson, as shown in Figs. 3 and 4. The consistency is established on the fact that the maximum mass of neutron stars is dominated by the high-density behavior of the EOS. In the
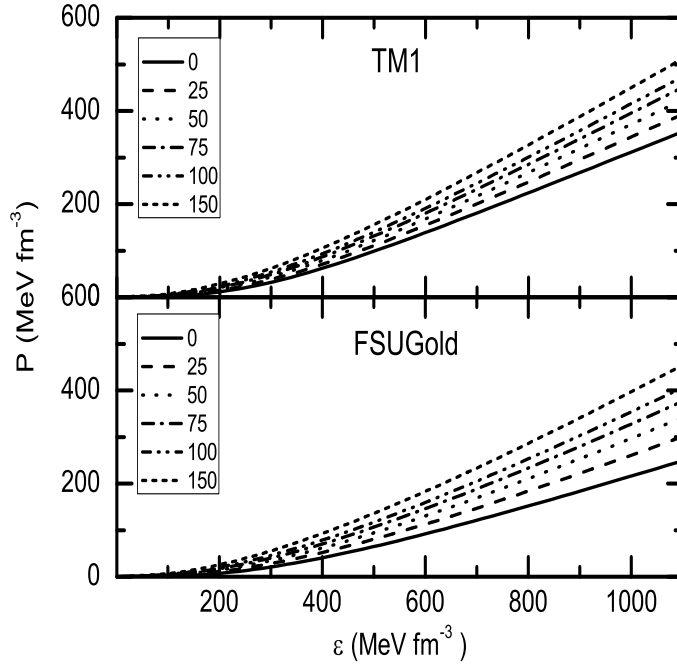
FIG. 4: The same as in Fig. 3 but for the RMF models TM1 and FSUGold.

past, a few neutron stars with large masses around $2M_\odot$ had been observed [53–55]. Though it can have improvements in experimental aspects, the observation of neutron stars with large masses is not so scarce. Recently, the mass of the LMXB 4U1608-52 is measured to be $1.74M_\odot$ [56], and most recently a $2M_\odot$ neutron star J1614-2230 was measured through the Shapiro delay [57]. Note that the model FSUGold which is well consistent with the nuclear laboratory constraints just produce a maximum mass about $1.7M_\odot$ for the neutron star without hyperons, whereas the hyperonization can further reduce the maximum mass to a value below $1.4M_\odot$. In this case, the role of the U-boson is constructive in increasing the maximum mass of neutron stars, either as the EOS is softened by the creation of new degrees of freedom, or the EOS is too soft to obtain a large maximum mass.

On the other hand, the radius of neutron stars is primarily determined by the EOS in the lower density region of $1\rho_0$ to $2\rho_0$, see Refs.[1, 4] and references therein. Because the symmetry energy in this density region offers the most important gradient of the pressure in pure neutron matter, the density dependence of the symmetry energy plays a crucial role in determining the radius of neutron stars. While in the present case the pressure in the lower density region is increased appreciably by the U-boson, it is not surprising that the sensitive variation of the neutron star radius is obtained accordingly. This is similar to the non-relativistic case in Ref. [20]. In fact, the radius of neutron stars relies sensitively on the stiffness of the EOS. Thus, the stiffening of the EOS caused by the U-boson gives rise to a significant increase of the radius. Concretely, we can see from Fig. 6 that the larger rise of the radius comes up with the more apparent stiffening role of the U-boson in softer
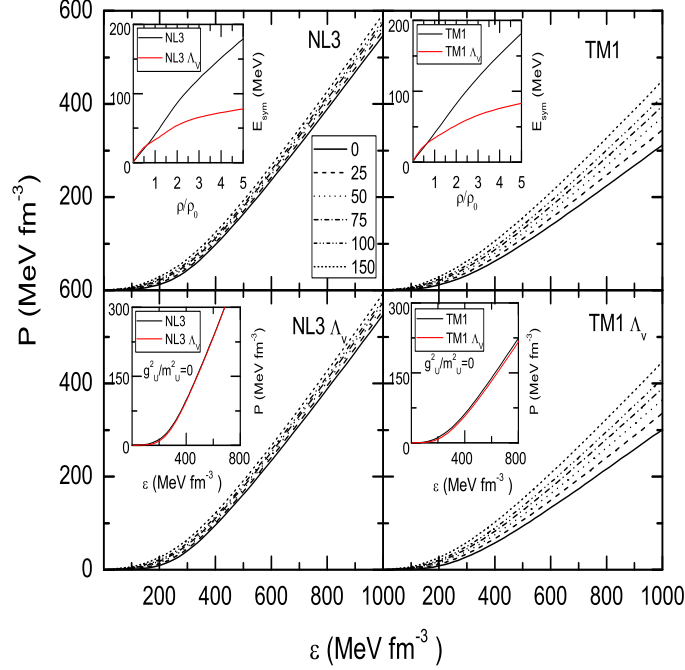
FIG. 5: (Color online) The same as in Fig. 3 but to exhibit the difference between the cases with and without the modification to the symmetry energy. Left panels represent the results with the NL3 and NL3Λ_V, and right panels are the results with the TM1 and TM1Λ_V. Different density dependencies of the symmetry energy are drawn in the insets of upper panels, while given in the insets of lower panels are the EOS of two cases in the absence of the U-boson.

models. It is known that the radius of neutron stars extracted from the observation can have a wide range due to the uncertainties of the distance measurement and theoretical models used for the spectrum analyses [1, 58–60]. A more precise extraction of the neutron star radius, probably through the coincident measurements, thus becomes very significant, because it can test the non-Newtonian gravity due to its promising sensitivity to the star radius.

To stress the role of the U-boson in the maximum mass and radius of neutron stars, we depict in Fig. 7 the M-R relation for various models with and without the U-boson. Here, for the case with the inclusion of the U-boson, the calculation is performed with $(g_u/m_u)^2 = 100 GeV^{-2}$. It is seen clearly that the large difference in maximum masses with various types of models can be reduced largely by the U-boson with suitable parameter $(g_u/m_u)^2$. We can see once again that the reduction of the difference is mainly attributed to the role of the U-boson in the models featuring much softer EOS's. Interestingly, we see that the uncertainty of the radius for a canonical neutron star (with the mass $1.4 M_\odot$) can also be reduced by the U-boson.

In view of interesting and significant roles of the U-boson, we may say that the task to look for the U-boson and further confirm the non-Newtonian gravity is also confronted. The recent experimental constraints on the relationship between parameters α (g_u) and λ (m_u) can be found in Ref. [23]. To recover the stability of neutron stars using the EOS constrained by the FOPI/GSI data [18], the
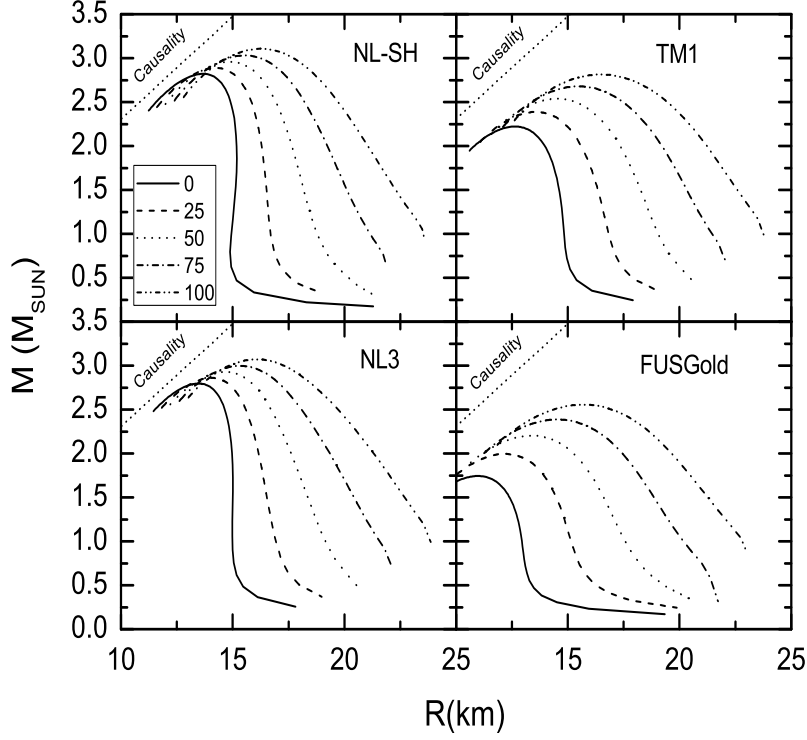
FIG. 6: The mass-radius relation of neutron stars with various models. The U-boson is included with various ratio parameters of $(g_u/m_u)^2$.
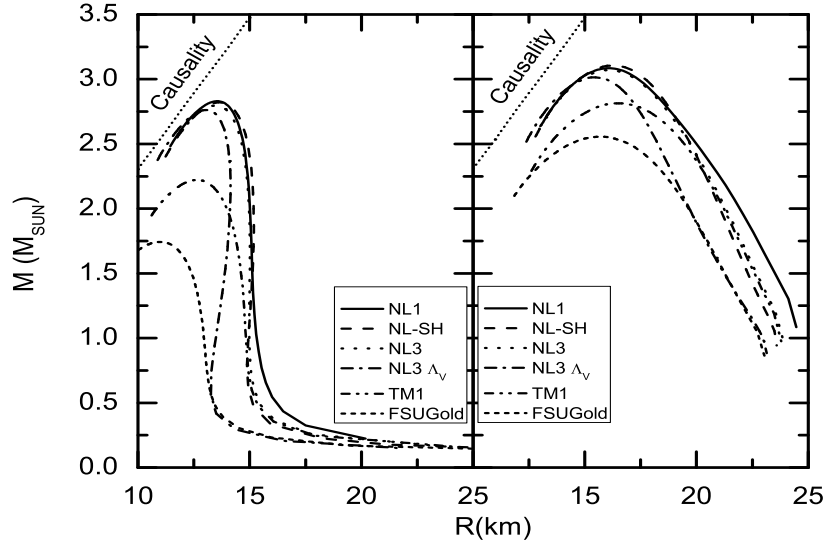

FIG. 7: Mass-radius relations for various models with the $(g_u/m_u)^2 = 0 GeV^{-2}$ (left panel) and the $(g_u/m_u)^2 = 100 GeV^{-2}$ (right panel).

ratio $(g_u/m_u)^2 \sim 100 GeV^{-2}$ was found to be needed [20]. In this work, the effect of the U-boson is investigated within the parameter region $(g_u/m_u)^2 = 0 \sim 100 GeV^{-2}$. To avoid the visible effect beyond low energy constraints in finite nuclei, with these values of the ratio parameter we may estimate that the mass of the U-boson should be of order below $1 MeV$ with the coupling strength

being almost or at least three orders less than the fine-structure constant, while these estimated orders can be compatible with parameter regions allowed by a few experimental constraints, see Ref. [23]. We expect that more precision experiments will be performed to better determine or exclude the parameter regions for the non-Newtonian gravity.

At last, it is interesting to discuss the relevance between the parameters of the non-Newtonian gravity touched upon in this work and the solution to the dark matter problem. In order to explain the flatness of the rotational curve of galactic spirals, one needs to assume the non-luminous dark matter being the additional gravitational source. Alternatively, the Newtonian gravity that was well tested in the solar system may be assumed to fail at the large distance scales of galaxies, and hence the Newtonian gravity should be modified to be the non-Newtonian one [61]. The Yukawa-type modification to the Newtonian gravity due to the boson exchange may possibly be considered as a candidate to solve the dark matter problem. In this work, the vector coupling of the U-boson that is restrained by the U(1) symmetry produces a repulsion other than the anticipated attraction. We may thus suppose to solve the dark matter problem through the introduction of light scalar bosons. However, since the flatness of the rotational curve requires a supplemental force roughly linear inversely in the distance from the center of the galaxy, even if the light scalar boson is assumed to provide the needed attraction in one region, the exponential suppression factor of the Yukawa-type potential (see Eq.(4)) actually inhibits the reproduction of the rotational curve in other regions. In deed, in addition to the introduction of the light scalar boson, more considerations are necessary to solve the dark matter problem [62]. On the other hand, we may explore the constraints from the effect of the U-boson on the dark matter. However, the coupling of the U-boson with the dark matter candidates should be assumed to be much stronger than that with the normal particles to explain the $511 keV$ γ-ray observation while simultaneously compatible with the low-energy constraints [25–28]. To sum up, we are presently not able to restrain the parameters of the non-Newtonian gravity originated from the U-boson exchange in this work directly by using the effect of the U-boson on the dark matter and/or the solution to the dark matter problem with the modified Newtonian dynamics. Nonetheless, this deserves further exploration. For instance, the further first-principle understanding of the underlying origin of the difference in the U-boson couplings to normal and dark matter particles may open possibility to extract constraints on the parameters of the non-Newtonian gravity.

IV. SUMMARY

We have studied in this work the effects of the U-boson in RMF models on the equation of state and subsequently the consequence in neutron stars. All RMF models are chosen to have similarly nice reproduction of saturation properties and ground-state properties of finite nuclei, whereas they

can give rise to a significantly large difference in EOS's at high densities and mass-radius relations of neutron stars. Interestingly, we find that the U-boson in models with much softer EOS plays a much more significant role in increasing the maximum mass of neutron stars. The distinction can be attributed analytically to the different modification caused by the U-boson in soft and stiff models to the pressure. Thus, the inclusion of the U-boson may allow the existence of the non-nucleonic degrees of freedom in the interior of large mass neutron stars initiated with the favorably soft EOS of normal nuclear matter. In addition, it is worth notifying that the radius of canonical neutron stars in all models can be sensitively modified by the U-boson due to its stiffening role in the EOS. Meanwhile, the difference in the mass-radius relations predicted by various models can favorably be reduced by increasing the coupling strength between the U-boson and baryons. At last, constraints on the parameters of the non-Newtonian gravity are discussed. Presently, we have not found the direct relevance between the parameters of the non-Newtonian gravity originated from the U-boson exchange and its effect on the dark matter concerning the dark matter problem. Together with the future coincident measurements and more precise extraction of the mass and radius of neutron stars, the sensitive role of the U-boson in the M-R relation may be helpfully used to test the physics beyond the standard model and consequently the existence of the non-Newtonian gravity in the dense neutron star.

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