Super-soft symmetry energy encountering non-Newtonian gravity in neutron stars

De-Hua Wen, Bao-An Li*, and Lie-Wen Chen

1Department of Physics, South China University of Technology, Guangzhou 510641, P.R. China
2Department of Physics and Astronomy, Texas A&M University-Commerce, Commerce, Texas 75429-3011, USA
3Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, P.R. China

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Considering the non-Newtonian gravity proposed in the grand unification theories, we show that the stability and observed global properties of neutron stars can not rule out the super-soft nuclear symmetry energies at supra-saturation densities. The degree of possible violation of the Inverse-Square-Law of gravity in neutron stars is estimated using an Equation of State (EOS) of neutron-rich nuclear matter consistent with the available terrestrial laboratory data.

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The density dependence of nuclear symmetry energy $E_{\text{sym}}(\rho)$ is an important ingredient for understanding many interesting phenomena in astrophysics, cosmology and nuclear physics. However, theoretical predictions on the $E_{\text{sym}}(\rho)$ especially at supra-saturation densities are currently rather diverse. Unfortunately, there is no known first-principle guiding the high-density behavior of the $E_{\text{sym}}(\rho)$. Presently, while many theories, see, e.g., refs. 4 13 14 15 16 17, predict that the $E_{\text{sym}}(\rho)$ increases continuously at all densities, many other models, see, e.g., refs. 2 3 8 9 10 11 12 13, predict that the $E_{\text{sym}}(\rho)$ first increases and then decreases above certain supra-saturation densities. The $E_{\text{sym}}(\rho)$ may even become negative at high densities 2 3 8 9 10 11 12 13 14 15 16 17. This latter kind of symmetry energy functions are generally regarded as being soft. Some (e.g., the UV14+TNI in 20 and group II in 24) of them can describe very well all observed properties of neutron stars (NSs). However, the super-soft ones (e.g., the original Gogny-Hartree-Fock (GHF) prediction 24 and group III in 24) that quickly drops to zero around three times the saturation density either can not keep the NSs stable or predict maximum NS masses significantly below 1.4 M$_\odot$ depending on the EOS used for symmetric nuclear matter. Given the above theoretical situation, experimental indications on the high density $E_{\text{sym}}(\rho)$ are thus utmost important. Very interestingly, circumstantial evidence for a super-soft $E_{\text{sym}}(\rho)$ 33 was found very recently from analyzing the FOPI/GSI experimental data on the $\pi^-/\pi^+$ ratio in relativistic heavy-ion collisions 34 within a transport model 35 using the MDI (Momentum-Dependent-Interaction) EOS 27. While the symmetric part of the MDI EOS is consistent with the existing terrestrial nuclear laboratory data 8 8, the total pressure of NS matter obtained using the super-soft $E_{\text{sym}}(\rho)$ (which is actually the original GHF prediction) preferred by the FOPI/GSI data can not keep neutron stars stable.

Among possibly many important ramifications in astrophysics and cosmology, this finding posts immediately a serious scientific challenge: how can the NSs be stable with such kind of super-soft symmetry energies? In fact, this question has been raised repeatedly and the answer has been negative long before any experimental indication was available. In the literature, the super-soft symmetry energies were often regarded by some people as either “unpleasant”, see, e.g., 23, or “unphysical”, see, e.g., 24 36 37. These assertions, of course, are all based on the assumption that gravity is well understood. However, it is really remarkable that gravity, despite being the first to be discovered, is actually still considered by far the most poorly understood force 38 39 40. In fact, in pursuit of unifying gravity with the three other fundamental forces, conventional understanding about gravity has to be modified due to either the geometrical effect of the extra space-time dimensions predicted by string theories and/or the exchange of the weakly interacting bosons newly proposed in the super-symmetric extension of the Standard Model, see, e.g., refs. 41 42 for reviews. Consequently, the Inverse-Square-Law (ISL) of gravity is expected to be violated. In stable neutron stars at $\beta$ equilibrium which is determined by the weak and electromagnetic interactions, the gravity has to be balanced by the strong interaction. Neutron stars are thus a natural testing ground of grand unification theories. In this Letter, we show that the super-soft $E_{\text{sym}}(\rho)$ preferred by the FOPI/GSI data can readily keep neutron stars stable if the non-Newtonian gravity is considered.

The deviation from the ISL of gravity can be characterized effectively by adding a Yukawa term to the normal gravitational potential 43 44, i.e.,

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

(1)

where $\alpha$ is a dimensionless strength parameter, $\lambda$ is the length scale and $G_\infty$ is the universal gravitational constant. Alternatively, the Yukawa term can also be considered as due to the putative “fifth force” 41 42 43 coexisting with gravity or a non-universal gravitational “constant” 41 43 of $G(r) = G_\infty[1 + \alpha e^{-r/\lambda}(1 + r/\lambda)]$. In the scalar/vector boson exchange picture,
\[ \alpha = \pm g^2/(4\pi G_m n_b^2) \] and \( \lambda = 1/\mu \) (in natural units). The \( g^2 \), \( \mu \) and \( m_b \) are the boson-baryon coupling constant, the boson and baryon mass, respectively. To reduce gravity from the ISL, the exchange of a vector boson is necessary. It is worth noting that a neutral spin-1 vector U-boson has been a favorite candidate. It is very weakly coupled to baryons \[ 46], can mediate the interactions among Dark Matter (DM) candidates \[ 47, 48] and has been used to explain the 511 keV \( \gamma \)-ray observation from the galactic bulge \[ 49, 50, 51].

According to Fujii \[ 52], the Yukawa term is simply part of the matter system in general relativity. Consequently, the Einstein equation remains the same and only the EOS is modified. Within the mean-field approximation, the extra energy density due to the Yukawa term is \[ 44 \[ 46] \]

\[ \varepsilon_{\text{un}} = \frac{1}{2V} \int \rho(\vec{x}_1) \frac{g^2}{4\pi} e^{-\mu r} \rho(\vec{x}_2) d\vec{x}_1 d\vec{x}_2 = \frac{1}{2} \frac{g^2}{\mu^2} \rho^2 , \]

where \( V \) is the normalization volume, \( \rho \) is the baryon number density and \( r = |\vec{x}_1 - \vec{x}_2| \). The corresponding addition to the pressure is then \( P_{UB} = \frac{1}{2} \frac{g^2}{\mu^2} \left( 1 - \frac{2\rho}{\rho_0} \frac{\partial \mu}{\partial \rho} \right) \).

Assuming a constant boson mass independent of the density, one obtains \( P_{UB} = \varepsilon_{UB} = \frac{1}{2} \frac{g^2}{\mu^2} \rho^2 \). For the purposes of the present study, it is sufficient to consider neutron stars as simply consist of neutrons (n), protons (p) and electrons (e). Including the Yukawa term the total pressure inside neutron stars is \( P = P_{\text{ne}} + P_{UB} \). For the inner and outer crusts we use \( P_{\text{ne}} \) the EOS of Carriere et al. \[ 53 \] and that of Baym et al. \[ 54 \], respectively. They are smoothly connected to the EOS in the core \[ 55 \]. For the latter we use \( P_{\text{ne}}(\rho, \delta) = \rho^2 \left[ dE_0/d\rho + dE_{\text{sym}}/d\rho \delta^2 \right] + \frac{1}{2}(1-\delta)\rho_E\text{sym}(\rho) \). The value of the isospin asymmetry \( \delta \) at \( \beta \) equilibrium is determined by the chemical equilibrium condition \( \mu_e = \mu_n - \mu_p = 4\delta E_{\text{sym}}(\rho) \) and the charge neutrality requirement \( \rho_e = \frac{1}{3}(1-\delta)\rho \). The \( E_0(\rho) \) and \( E_{\text{sym}}(\rho) \) obtained consistently within the modified GHF approximation are \[ 27, 55 \], respectively,

\[ E_0(\rho) = \frac{8\pi}{9m_h^3\rho} p_f^2 + \frac{\rho}{4\rho_0} \cdot (-216.55) + \frac{B}{\sigma + 1} \left( \frac{\rho}{\rho_0} \right)^\sigma + \frac{1}{3\rho_0}(C_l + C_u) \left( \frac{4\pi}{h^2} \right)^2 \Lambda^2 \times \left[ p_f^2 (6p_f^2 - \Lambda^2) - 8\Lambda p_f^2 \arctan \left( \frac{2p_f}{\Lambda} \right) + \frac{2}{4}(\Lambda^4 + 12\Lambda^2 p_f^2) \ln \left( \frac{4p_f^2 + \Lambda^2}{\Lambda^2} \right) \right] , \]

\[ E_{\text{sym}}(\rho) = \frac{8\pi}{9m_h^3\rho} p_f^2 + \frac{\rho}{4\rho_0} \cdot [-24.59 + 4Bx/(\sigma + 1)] - \frac{Bx}{\sigma + 1} \left( \frac{\rho}{\rho_0} \right)^\sigma + \frac{C_l}{9\rho_0} \left( \frac{4\pi}{h^2} \right)^2 \Lambda^2 \left[ 4p_f^2 - \Lambda^2 p_f^2 \ln \left( \frac{4p_f^2 + \Lambda^2}{\Lambda^2} \right) \right] + \frac{C_u}{9\rho_0} \left( \frac{4\pi}{h^2} \right)^2 \Lambda^2 \left[ 4p_f^2 - p_f^2 (4p_f^2 + \Lambda^2) \ln \left( \frac{4p_f^2 + \Lambda^2}{\Lambda^2} \right) \right] , \tag{3} \]

where \( p_f = b(3\pi^2 \frac{2}{3})^{1/3} \) is the Fermi momentum for symmetric nuclear matter at density \( \rho \). The coefficients \( A_u(x) = -95.98 - x^{2B/(\sigma+1)} \) and \( A_l(x) = -120.57 + x^{2B/(\sigma+1)} \). The values of the parameters are \( \sigma = 4/3 \), \( B = 106.35 \) MeV, \( C_l = -11.70 \) MeV, \( C_u = -103.40 \) MeV and \( \Lambda = p_f \equiv p_f(\rho_0) \) \[ 27 \]. The resulting symmetric EOS contribution \( dE_0/d\rho \) to the pressure is consistent with that extracted from studying kaon production and nuclear collectivity flow in relativistic heavy-ion collisions using hadronic transport models assuming no hadron to Quark-Gluon Plasma phase transition up to about 5\( \rho_0 \) \[ 4 \[ 8 \]. The parameter \( x \) in Eq. \[ 3 \] was introduced to vary the density dependence of the \( E_{\text{sym}}(\rho) \) without changing any property of symmetric nuclear matter and the value of \( E_{\text{sym}}(\rho_0) = 31 \) MeV \[ 27 \]. Shown in the inset of Fig.1 are two typical \( E_{\text{sym}}(\rho) \) denoted as MDIx1 and MDIx0 obtained by using \( x = 1 \) and \( x = 0 \), respectively. While the MDIx0 \( E_{\text{sym}}(\rho) \) increases continuously, the MDIx1 \( E_{\text{sym}}(\rho) \) becomes negative above 3\( \rho_0 \). Only the MDIx1 \( E_{\text{sym}}(\rho) \) can reproduce the FOPI/GSI pion production data within the transport model analysis \[ 33 \]. It is seen that the corresponding MDIx1 pressure decreases with increasing density as shown with the lowest curve in Fig. 1. However, the Yukawa term makes the pressure grow continuously with increasing density with a value of \( g^2/\mu^2 \) higher than about 10 GeV\(^{-2} \).

Shown in Fig. 2 is the mass-radius relation of static neutron stars obtained from solving the Tolman-Oppenheimer-Volkoff (TOV) equation using the MDIx1 \( E_{\text{sym}}(\rho) \) and various values for \( g^2/\mu^2 \). The result obtained using the MDIx0 without including the Yukawa term is included as a reference \[ 58 \]. The causality \[ 8 \] and rotational constraint \[ 57 \] are also shown. The Keplerian (mass-shedding) frequency is approximately \[ 57 \]

\[ \nu_k \approx 1.08 \left( \frac{M}{M_{\odot}} \right)^{1/2} \left( \frac{R}{10 \text{ km}} \right)^{-3/2} \text{ kHz} \]. So far, the fastest pulsar observed is the J1748-2446ad spinning at 716 Hz \[ 59 \]. Taking 716 Hz as the Keplerian frequency, the M-R relation is restricted to the left side of the rotational
the moment of inertia, will be very useful in setting as-
measurements related to the mass distribution, such as
accurate measurement of neutron star radii, additional
|
| can have a maximum mass between 1.4 and 2.5 M⊙−
| be higher than about 50 GeV
g| with a maximum mass above 1.
| 150 GeV−
| However, significantly larger
| the MDIx1 | the Yukawa contribution. The discovery of the double-pulsar system PSR J0737-3039
| Ak&B provides a great opportunity to determine ac-
| accurately the moment of inertia IA of the star A [62, 63].
| Our results shown here add to the importance of mea-
| suring the moment of inertia accurately.

To constrain the values of α and λ has been a long-
standing goal of many terrestrial experiments and astro-
physical observations as limits on them may provide
useful guidance for developing grand unification theories,
see, e.g., refs. [41, 42, 43, 54, 65, 66, 67, 68, 69, 70]. These
studies have estimated various upper limits on the α. In
the range of α = 10−10−1018 and λ = 1015−10−14 m,
there is a clear trend of increased strength α at shorter
length λ. What we have constrained is the value of g2/µ2
or equivalently the |α|λ2 from the pressure necessary to
support both static neutron stars and the fastest pulsars.
While we expect that the range parameter λ has to be
much larger (smaller) than the radii of finite nuclei (neu-
tron stars), we can not set separate constraints on the
values of α and λ. Compared to other efforts to con-
strain the α and λ, our study here is unique in that the
estimated minimum value of g2/µ2 is a lower limit sati-
fying all known constraints from both terrestrial nuclear
experiments and observations of global properties of neu-
tron stars. Moreover, very interestingly, our estimated
range of g2/µ2 overlaps well with the upper limits esti-
| mated from analyzing the neutron-proton and neutron-
| lead scattering data in the range of λ ≈ 10−14−10−8 m
| 70, 71, 72, 73.

In summary, neutron stars are a natural testing ground
of grand unification theories of fundamental forces. Con-
sidering the possible violation of the ISL of gravity, the
stability and observed properties of NSs can not rule out
super-soft symmetry energies at supra-saturation den-
sities. Given the uncertainties and model dependence
involved in extracting information about the EOS and
symmetry energy from heavy-ion reactions, it is very im-
portant to test the possible super-soft symmetry energy

limit. The latter restricts the value of g2/µ2 to less than
150 GeV−2. It is seen that to produce a neutron star with
a maximum mass above 1.4 M⊙, the g2/µ2 has to be higher than about 50 GeV−2. More specifically, with
the MDIx1 E_{sym}(ρ) and the g2/µ2 = 50−150 GeV−2, or
equivalently |α|λ2 = (2.6 − 7.8) × 10^{-5} m², neutron stars
can have a maximum mass between 1.4 and 2.5 M⊙ and
a corresponding radius between 12 and 18 km.

For canonical neutron stars of 1.4 M⊙, the radius is
quite sensitive to the g2/µ2 value used. Thus, besides the
accurate measurement of neutron star radii, additional
measurements related to the mass distribution, such as
the moment of inertia, will be very useful in setting astro-
physically constraints on the E_{sym}(ρ) and g2/µ2. Ac-
| cording to Lattimer and Schutz [64, at the slow rotation
| limit the moment of inertia can be well approximated as
| I ≈ (0.237 ± 0.008)MR² [1 + 4.3 \frac{M}{M_{⊙}} \frac{km}{M_{C}} + 90 \left( \frac{M}{M_{⊙}} \frac{km}{M_{C}} \right)^4].
| Shown in Fig. 3 is the I as a function of M. For
| M = 1.4 M_{⊙}, the MDIx0 without the Yukawa con-
| contribution gives an I no more than 1.8 × 10^{38} kg \cdot m^2 [60].
| However, significantly larger I values are obtained with
| the MDIx1 E_{sym}(ρ) and the Yukawa contribution. The
| discovery of the double-pulsar system PSR J0737-3039
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![FIG. 1: (Color online)The inset shows two typical examples
(3Dx0 and 3Dx1) of the density dependence of the nuclear
symmetry energy. The 3Dx1 (3Dx0) EOS with (without) the
Yukawa contribution using different values of the
\( g^2/\mu^2 \) in units of GeV^{-2} are shown.](image1)

![FIG. 2: (Color online) The mass-radius relation of static neu-
tron stars with the 3Dx1 (3Dx0) EOS with (without) the
Yukawa contribution. The static neutron star sequences con-
strained by the rotational frequency 716 Hz of the J1748-
2446ad [56] are taken from Haensel et al. [57].](image2)

![FIG. 3: (Color online) The momenta of inertia of neutron
stars with the 3Dx1 (3Dx0) E_{sym}(\rho) with (without) the
Yukawa contribution. The numbers above the lines are the
\( g^2/\mu^2 \) values in units of GeV^{-2}.](image3)
at supra-saturation densities using several observables simultaneously from independent experiments analyzed using different models. If confirmed, it may point towards a violation of the ISL in neutron stars.

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