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THE INFLUENCE OF THE SYMMETRY ENERGY ON THE STRUCTURE OF HYPERON STARS*

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The analysis of the density dependence of the nuclear symmetry energy in strangeness-rich nuclear matter was done. Calculations were performed on the basis of models with significant differences in the vector meson sector.

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1. Introduction

The nuclear symmetry energy is a quantity especially important for neutron stars as it is directly related to the nuclear matter equation of state (EoS), which, in turn, unambiguously determines the EoS of the uniform neutron star matter. Neutron star matter is characterized by a high value of the neutron–proton asymmetry, which is settled by the β-equilibrium condition. At sufficiently high density relevant for the inner core of a neutron star the equilibrium conditions predict the appearance of additional degrees of freedom with hyperons as the most obvious candidates, thus it is expected that symmetry energy being encoded in the EoS of strangeness-rich nuclear matter influences many properties of neutron stars. Experimental determination of the symmetry energy is beset by problems that are connected with the fact that the symmetry energy is not a physical observable and the only experimentally accessible information comes from indirect measurements [1].

2. Symmetry energy — definition

Nuclear matter is regarded as an infinite system of nucleons with fixed neutron and proton numbers and no Coulomb interaction. The relative

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neutron excess defined as the neutron–proton asymmetry parameter $\delta_{\rm a}$ has the form:

$$\delta_{\rm a} = \frac{n_n - n_p}{n_n + n_p}\,, \tag{1}$$

where n_n and n_p denote the neutron and proton number densities respectively, the sum $n_n + n_p = n_B$ stands for the total baryon number density. In the case of symmetric nuclear matter, the EoS at density near saturation density n_0 is relatively well defined and controlled by experiments such as the giant monopole resonances of finite nuclei, collective flows and subthreshold kaon production in relativistic nucleus–nucleus collisions [2]. However, our understanding of the form of the EoS of asymmetric nuclear matter is still inadequate to correctly solve essential problems in nuclear physics and astrophysics. The symmetry energy being the decisive part of the nuclear matter EoS has encoded the isopin dependent part of nuclear interactions. In general, in two component nucleon system the EoS considered as the energy per particle

$$\varepsilon(n_B, \delta_{\rm a}) = \frac{E(n_B, \delta_{\rm a})}{n_B} \tag{2}$$

is a function of baryon number density n_B and the asymmetry parameter $\delta_{\rm a}$; $E(n_B, \delta_{\rm a})$ in equation (2) denotes the total energy of the nuclear system.

Considering the model of nuclear matter consisting of N nucleons, the symmetry energy provides basic information about energy difference between states with different neutron–proton asymmetry and is defined as the energy difference of the state with specified proton and neutron composition, and the one with equal number of neutrons and protons (symmetric nuclear matter) and can be written as [3]:

$$E_{\rm sym}(N_p, N_n) = E(N_p, N_n) - E(N_p = N/2, N_n = N/2)\,. \tag{3}$$

Equation (3) written in terms of the energy density takes the following form:

$$\varepsilon_{\rm sym}(n_B, \delta_{\rm a}) = \varepsilon(n_B, \delta_{\rm a}) - \varepsilon(n_B, \delta_{\rm a} = 0)\,. \tag{4}$$

Expanding the energy per particle of asymmetric nuclear matter in a Taylor series in $\delta_{\rm a}$:

$$\varepsilon(n_B, \delta_{\rm a}) = \varepsilon(n_B, 0) + S_2(n_B)\delta_{\rm a}^2 + S_4(n_B)\delta_{\rm a}^4 + \ldots \tag{5}$$

and keeping only the term quadratic in the asymmetry parameter $\delta_{\rm a}$, the well-known parabolic approximation can be obtained. In this case, the symmetry energy $\varepsilon_{\rm sym}(n_B, \delta_{\rm a}) \approx n_B S_2(n_B)\delta_{\rm a}^2$ and this approximation provides good description of asymmetric nuclear matter near the saturation density n_0. However, omission of the higher order terms may lead to inaccurate estimates of the properties of β-equilibrated neutron star matter. The symmetry energy $E_{\rm sym}(n_B)$ is probed by experiments near nuclear saturation density n_0 thus, it is reasonable to represent $E_{\rm sym}(n_B) \equiv S_2(n_B)$ as a Taylor series near n_0. Defining the parameter $x = (n_B - n_0)/3$, the following expression can be obtained:

$$S_2(n_B) \simeq S_v + Lx + \frac{K_{\rm sym}}{2}x^2 + \dots\,, \tag{6}$$

where L and $K_{\rm sym}$ characterizes respectively the slope and curvature of the symmetry energy. Considering the strangeness-rich nuclear matter, the analysis of the density dependence of the symmetry energy may be done analogously as in the case of two-component nucleon matter. Assuming a system of nucleons and hyperons, the symmetry energy can be defined as:

$$\bar{\varepsilon}_{\rm sym}(n_B, \delta_{\rm a}, \delta_S) = \varepsilon(n_B, \delta_{\rm a}, \delta_S) - \varepsilon(n_B, \delta_{\rm a} = 0, \delta_S)\,, \tag{7}$$

where $n_B = n_N + n_Y$, n_N and n_Y denote the nucleon and hyperon number densities, respectively. The strangeness content of the nuclear matter is specified by the parameter δ_S, which is defined as $\delta_S = \sum_i |s_i| n_i/n_B$, where the s_i is the strangeness of baryon i. Thus, the case of nucleon matter is recovered setting $\delta_S = 0$. It is evident from equation (7) that the density dependence of the symmetry energy will be modified in the presence of hyperons.

3. The model

The problem of the density dependence of the symmetry energy is analysed on the basis of the Walecka model [4]. Calculations of the equation of state have been done in the mean field approach. In this approximation, meson fields are separated into classical mean field values and quantum fluctuations, which are neglected in the ground state. In the case of nucleon matter relevant degrees of freedom are neutrons and protons interacting through the exchange of scalar σ and vector ω, ρ meson fields. The general form of the Lagrangian $\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\rm int}^{S=0}$ includes the part $\mathcal{L}_{\rm int}^{S=0}$, which describes the non-linear self and mixed vector meson interactions. In the case of nucleon system, it has the following form:

$$\mathcal{L}_{\rm int}^{S=0} = -\tfrac{1}{3}g_3\sigma^3 - \tfrac{1}{4}g_4\sigma^4 + \tfrac{1}{4}c_3\left(\omega^\mu\omega_\mu\right)^2 + \Lambda_{\rm V}\left(g_\omega g_\rho\right)^2\left(\omega^\mu\omega_\mu\right)\left(\rho^{\mu a}\rho^a_\mu\right)\,. \tag{8}$$

As neutron star matter is characterised by a high value of the neutron–proton asymmetry, the term that describes the ω–ρ coupling is particularly important. It gives the ability to modify the high density component of the symmetry energy. In this case, the isovector sector is characterized by two parameters g_ρ and Λ_{V}, which must be adjusted in order to reproduce the symmetry energy $E_{\mathrm{sym}} = 25.68$ MeV at $k_F = 1.15\ \mathrm{fm}^{-1}$ [5].

Description of strangeness-rich nuclear matter requires taking into consideration additional degrees of freedom. Thus, in addition to nucleons, the system includes strange baryons. The meson sector is extended by strange mesons, which are introduced to reproduce the hyperon–hyperon interactions. The considered model of nuclear matter was constructed within the framework of the non-linear realization of the chiral $\mathrm{SU}(3)_{\mathrm{L}} \times \mathrm{SU}(3)_{\mathrm{R}}$ symmetry. Details can be found in papers by Papazoglou *et al.* [6, 7]. The characteristic feature of this model is the extended vector meson sector that comprises different mixed vector meson couplings. This enables a more accurate description of asymmetric, strangeness-rich nuclear matter [8]. The interaction Lagrangian density at the mean field level can be written in a very general form:

$$\mathcal{L}_{\mathrm{int}}^{S\neq 0} = \sum_{i,j,k} \alpha(\Lambda_{\mathrm{V}})_{ijk} w^i r^j f^k \,, \tag{9}$$

where $\alpha(\Lambda_{\mathrm{V}})_{ijk}$ are parameters that described the strength of vector meson couplings. These parameters depend on the value of Λ_{V}, and in the case of nucleon matter, the ω–ρ mesons coupling constant takes the form: $\alpha(\Lambda_{\mathrm{V}})_{220} = (g_\omega g_\rho)^2 \Lambda_{\mathrm{V}}$. The form of the field equations indicates the isospin dependence of ω and ϕ vector mesons due to their couplings with the ρ meson field. Calculations of the explicit form of the interaction part of the symmetry energy leads to the following expression:

$$E_{\mathrm{sym}}^{\mathrm{int}}(n_B) = g_\rho n_B \frac{\left(3\alpha_{022}(\Lambda_{\mathrm{V}}) f^2 + m_\rho^2 + 2\left(g_\omega g_\rho\right)^2 \Lambda_{\mathrm{V}} w^2\right)}{4\left(2\alpha_{022}(\Lambda_{\mathrm{V}}) f^2 + m_\rho^2 + 2\left(g_\omega g_\rho\right)^2 \Lambda_{\mathrm{V}} w^2\right)^2} \,, \tag{10}$$

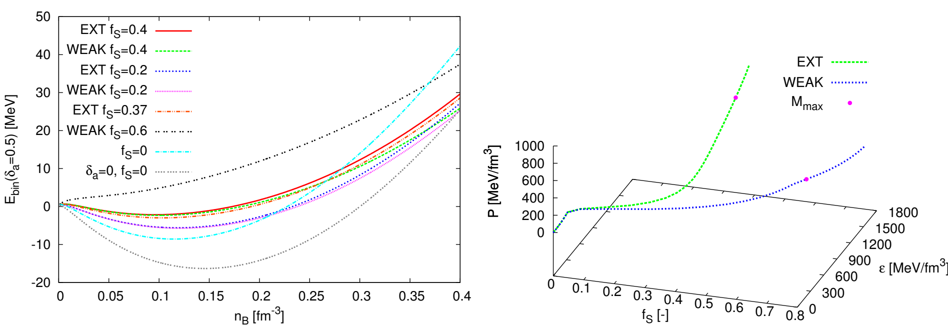
where $\alpha_{022}(\Lambda_{\mathrm{V}}) = \frac{3}{2} c_3 - (g_\omega g_\rho)^2 \Lambda_{\mathrm{V}}$ [9]. When the matter includes only nucleons, the well-known relation can be recovered

$$E_{\mathrm{sym}}^{\mathrm{int}}(n_B) = \frac{g_\rho n_B}{4\left(m_\rho^2 + 2(g_\omega g_\rho)^2 \Lambda_{\mathrm{V}} w^2\right)} \,. \tag{11}$$

The parameter Λ_{V} that determines the strength of the vector meson couplings allows one to modify the density dependence of the symmetry energy and in accordance with the low density expansion (6) changes the value of the slope parameter L. The case with $\Lambda_{\mathrm{V}} = 0$ leads to the rather high value of $L = 110$ MeV, whereas $\Lambda_{\mathrm{V}} = 0.0165$ gives experimentally acceptable results, which are in the range of 88 ± 25 MeV [10]. Calculations are based on the well-known TM1 parameter set [11].

4. Results and conclusions

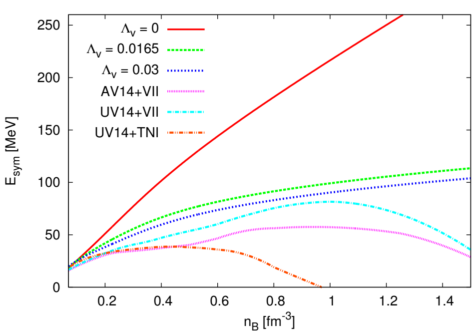
The density dependence of the binding energy was calculated for the asymmetric nuclear matter in the case of weak model (WEAK), when strange mesons are introduced in the minimal fashion, and nonlinear extended model (EXT), for the neutron–proton asymmetry $\delta_{\mathrm{a}} = 0.5$ and for the parameter $\Lambda_{\mathrm{V}} = 0.0165$. The value of the parameter Λ_{V} is justified by the fact that the extended model with $\Lambda_{\mathrm{V}} = 0.0165$ leads to the EoS that supports the 2 $M_{\odot}$ neutron star [8, 12, 13]. Results are collected in Fig. 1 (a). Individual lines represent binding energies obtained for different values of the strangeness fraction δ_S. For both models, the increasing value of δ_S leads to the weakly bound systems. For comparison, the results obtained for the symmetric matter and for asymmetric nucleon matter were also included. In Fig. 1 (b), the EoS and its dependence on the strangeness fraction δ_S is shown. Comparing the EoSs calculated on the basis of the weak and extended model, one can see significant differences in the achievable strangeness fractions. Thus, one can expect that the symmetry energy encoded in the EoS is also sensitive on the strangeness content of nuclear matter. Models of the EoSs with this very specific behaviour of the strangeness content give as a result different values of the maximum masses. Only the model with the extended vector meson sector leads to the EoS that satisfactorily reproduces the massive neutron stars.



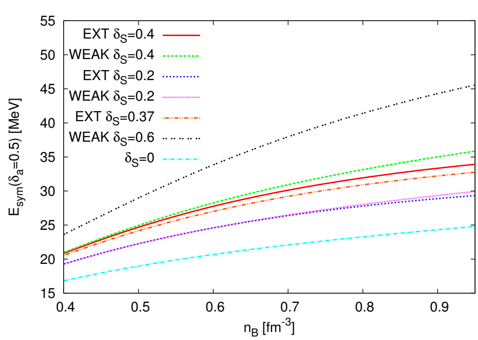
(a) (b)

Fig. 1. Left panel: Binding energy of the asymmetric hyperon-rich matter as a function of baryon density n_B, calculated for different values of the strangeness fraction δ_S. The results for the TM1-weak and TM1-extended models are included. Right panel: EoSs for hyperon-rich neutron star matter as a function of strangeness fraction. Dots represent the maximum mass configurations.

The symmetry energy was calculated basing on the binding energy. In panels of Fig. 2 (a) and Fig. 2 (b), the density dependence of the symmetry energy is shown. In the left panel, the results obtained for the nucleon matter is presented. Isovector sector comprises the ω–ρ meson interaction and the parameter Λ_{V} sets the strength of this ω–ρ coupling. In this case, the additional ω–ρ coupling alters the density dependence of the symmetry energy. The standard TM1 parameterisation without ω–ρ coupling gives as a result very stiff form of the symmetry energy. The inclusion of the ω–ρ coupling softens the symmetry energy. Calculations were done for rather high values of $\Lambda_{\mathrm{V}} = 0.0165$ and 0.03. The interaction between ω and ρ mesons leads to the solution, which approaches that obtained for the AV14 and UV14 models with the Urbana VII (UV VII) three-nucleon potential. For comparison, the form of the symmetry energy calculated for the UV14 plus TNI model was included [14]. In the right panel of Fig. 2, the form of the symmetry energy for the case of strangeness rich matter is depicted. Calculations were done for asymmetric nuclear matter for the same set of parameters: ($f_a = 0.5, \Lambda_{\mathrm{V}} = 0.0165$). Particular lines are parametrized by the strangeness fraction δ_S. The result obtained for the non-strange matter $\delta_S = 0$ is also presented. From this figure, it is evident that the density dependence of the symmetry energy is altered in the hyperon-rich environment. This specific form of the symmetry energy influences also other properties of neutron star matter and through this neutron star internal structure and composition.



(a) The nuclear matter.



(b) The hyperonic matter.

Fig. 2. Left panel: The density dependence of symmetry energy calculated for different values of parameter Λ_{V} and compared with the results obtained for the realistic nuclear potential models [14]. Right panel: The density dependence of symmetry energy calculated for chosen value of parameter $\Lambda_{\mathrm{V}} = 0.0165$ in the case of asymmetric strangeness-rich matter ($\delta_{\mathrm{a}} = 0.5$); $\delta_S = 0.37$ and $\delta_S = 0.6$ represent the maximal values of strangeness fraction achievable in the maximum mass configuration for extended and weak model, respectively.

REFERENCES

[1] D.V. Shetty, S.J. Yennello, *Pramana* **75**, 259 (2010).

[2] B.-J. Cai, L.-W. Chen, *Phys. Rev. C* **85**, 024302 (2012).

[3] H.K. Lee, M. Rho, *Int. J. Mod. Phys. E* **22**, 1330005 (2013).

[4] J.D. Walecka, *Theoretical Nuclear and Subnuclear Physics*, World Scientific, Singapore 2004.

[5] C.J. Horowitz, J. Piekarewicz, *Phys. Rev. Lett.* **86**, 5647 (2001).

[6] P. Papazoglou, *et al.*, *Phys. Rev. C* **57**, 2576 (1998).

[7] P. Papazoglou, *et al.*, *Phys. Rev. C* **59**, 411 (1999).

[8] I. Bednarek *et al.*, *Astron. Astrophys.* **543**, A157 (2012).

[9] I. Bednarek, R. Manka, *J. Phys. G* **36**, 095201 (2009).

[10] B.K. Agrawal, *Phys. Rev. C* **81**, 034323 (2010).

[11] Y. Sugahara, H. Toki, *Prog. Theor. Phys.* **92**, 803 (1994).

[12] P. Demorest *et al.*, *Nature* **467**, 1081 (2010).

[13] J. Antoniadis *et al.*, *Science* **340**, 6131 (2013).

[14] R.B. Wiringa, V. Fiks, *Phys. Rev. C* **38**, 1010 (1988).