IMPACT OF THE STRANGENESS ON THE STRUCTURE OF A NEUTRON STAR*

Ilona Bednarek, Monika Pieńkos

Institute of Physics, University of Silesia
Uniwersytecka 4, 40-007 Katowice, Poland

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The comparative analysis of the impact of strangeness on the structure and evolution of a neutron star was performed on the basis of two theoretical models. These models are indistinguishable for the density range relevant for the outer core of a neutron star. However, they gave qualitatively different results for the hyperon core of a neutron star.

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1. Introduction

Observations of binary millisecond pulsars J1614-2230 [1] and J0348+0432 [2] led to the precise estimation of neutron star masses: $(1.97\pm0.04)M_\odot$ and $(2.01\pm0.04)M_\odot$. The existence of such massive neutron stars entails important consequences for the equation of state (EoS) of dense nuclear matter and makes problematic the appearance of exotic particles such as hyperons and quarks in the very inner part of a neutron star. Construction of models that includes different exotic forms of matter often involves assumptions concerning the general structure of the Standard Model [3]. The description of the core of a neutron star is modelled on the basis of the EoS of dense nuclear matter in a neutron-rich environment [4] having a density that ranges from a few times the saturation density (n_0) to about an order of magnitude higher and at such densities hyperons are expected to emerge [5]. Analysis of the role and importance of strangeness was carried out just to consider the possibility of the existence of hyperons in neutron star interiors, and then to examine strangeness-rich neutron star internal structure and evolution.

A neutron star is formed as a result of successful supernova explosion and in the initial phase, just after gravitational collapse of the core of a massive star, the matter of proto-neutron star is hot and neutrino opaque. One can distinguish the low entropy ($s = 2$) core with rather high value

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of the electron lepton number $Y_{le} = (n_e + n_{\nu_e})/n_B \simeq 0.4$ surrounded by the high entropy envelope [6]. Thus, the analysis of a neutron star evolution bases on the model of warm asymmetric, non-zero strangeness nuclear matter with trapped neutrinos. All calculations have been done for two different models of strangeness-rich matter of a neutron star. The first one, called TM1-weak model, introduces strange mesons in the minimal form. The second one is extended by additional terms describing different vector meson couplings [7–10].

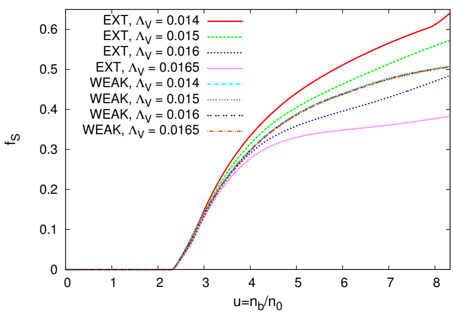
2. Results and conclusions

An imperfect knowledge of the EoS of dense, asymmetric nuclear matter causes uncertainty in theoretical estimation of neutron star parameters, especially in the case when hyperons are included. Results of observations that confirm the existence of massive neutron stars necessitate modification of the existing models of the EoSs. Theoretical analysis carried out on the basis of simple energetic considerations indicates the appearance of hyperons in neutron star matter at sufficiently high density. The value of the threshold density for hyperons is model dependent and results from the equilibrium conditions. The general feature of theoretical models that describe strangeness-rich matter of a neutron star is the significant softening of the EoSs. This, in turn, leads to the inconsistency between theoretical models and observations. Soft EoS gives as a result a low value of the maximum mass what is in contradiction with the results of observations [1, 2].

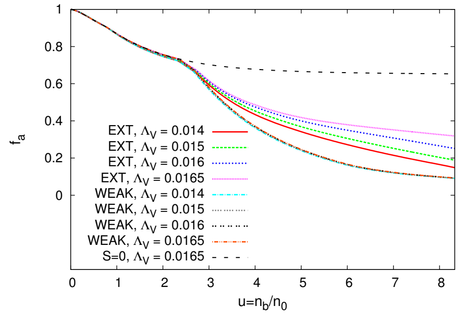
One of the proposed solutions to the problem of the existence of hyperons in the core of a neutron star are the theoretical models of the EoSs that introduce extra repulsion in the strange sector of the system. Such modification of the EoS significantly alters neutron star global parameters such as the mass and radius, internal structure and evolution. The model of the EoS that gives the value of the maximum mass consistent with the results of observations, is the one that introduces in the strange sector additional couplings between vector mesons. Defining the quantity δ_S that aim to evaluate the strangeness content of the system

$$\delta_S = \frac{\sum_B |S_B| n_B}{\sum_B n_B}\,, \tag{1}$$

the analysis of the properties of hyperon-rich neutron star matter was done. In the above equation, $\sum_B n_B = n_b$ is the baryon number density and S_B denotes the strangeness of baryon B. Through the field equations [11], δ_S depends on the value of coupling constants that determines the strength of hyperon–nucleon and hyperon–hyperon interactions. In Fig. 1 (a), the density dependence of the strangeness fraction calculated for the considered models is depicted. Particular cases refer to different values of the coupling constant $\Lambda_{\rm V}$. This coupling constants determines the slope of the symmetry energy of the nuclear matter [11]. In the case of the extended model, the influence of parameter $\Lambda_{\rm V}$ is evident, its increase lowers the value of δ_S at sufficiently high densities. The effect of the parameter $\Lambda_{\rm V}$ is negligible for the TM1-weak model. Figure 1 (b) shows the density dependence of the neutron–proton asymmetry. Calculations were done for the TM1-weak and TM1-extended model for different values of the parameter $\Lambda_{\rm V}$. In general, the presence of hyperons in nuclear matter lowers the value of asymmetry, for comparison, the result for non-strange matter is included ($S = 0$). The effect of parameter $\Lambda_{\rm V}$ is only important for the extended model. The highest value of $\Lambda_{\rm V}$ leads to the matter with higher neutron excess.



(a) The strangeness content of the system.



(b) The asymmetry parameter.

Fig. 1. The density dependence of the strangeness content of the system δ_S and neutron–proton asymmetry parameter $f_{\rm a} = (n_n - n_p)/(n_b)$ calculated for different values of parameter $\Lambda_{\rm V}$ for various models, n_n and n_p denote the neutron and proton number density, respectively.

Global neutron star parameters such as the mass and radius and the structure of a neutron star can be determined by the equation of hydrostatic equilibrium — the Tolman–Oppenheimer–Volkoff (TOV) equations

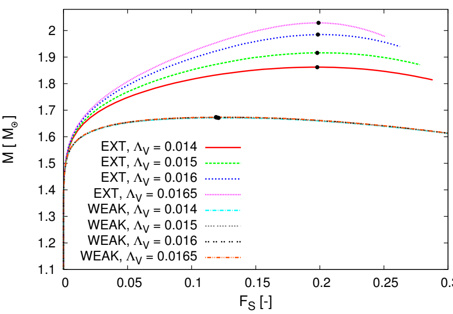
$$\begin{aligned}
\frac{d\mathcal{P}(r)}{dr} &= \frac{-G\left(\mathcal{E}(r)+\mathcal{P}(r)\right)\left(m(r)+4\pi r^3\mathcal{P}(r)\right)}{r^2\left(1-\frac{2Gm(r)}{r}\right)}\,,\\
\frac{dm(r)}{dr} &= 4\pi r^2\mathcal{E}(r)\,,\\
\frac{dn_b(r)}{dr} &= 4\pi r^2 n_b(r)\left(1-\frac{2Gm(r)}{r}\right)^{-1/2}\,, \qquad (2)
\end{aligned}$$

where m and n_b denote the enclosed gravitational mass and baryon number, respectively, $\mathcal{P}$ is the pressure and $\mathcal{E}$ is the total energy density. Solutions of the TOV equations were obtained for the set of EoSs, which differ in the strangeness content. For each model of a neutron star, a parameter which estimates the total strangeness content of a star was calculated. This quantity is given by the relation

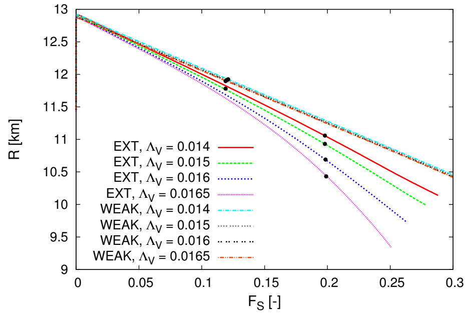
$$F_S = \frac{\sum_B |S_B| N_B}{\sum_B N_B}, \tag{3}$$

$$N_B = 4\pi \int_0^R r^2 \left(1 - \frac{2GM(r)}{c^2 r^2}\right)^{-1/2} n_B(r)\,. \tag{4}$$

Results are presented in Fig. 2. In the left panel, the mass–total strangeness content relation is shown. Dots represent the values of the maximum mass configurations obtained for the considered models, for different values of parameter $\Lambda_{\rm V}$. There is a significant difference between the results obtained in the TM1-weak and TM1-extended models. The effect of the parameter



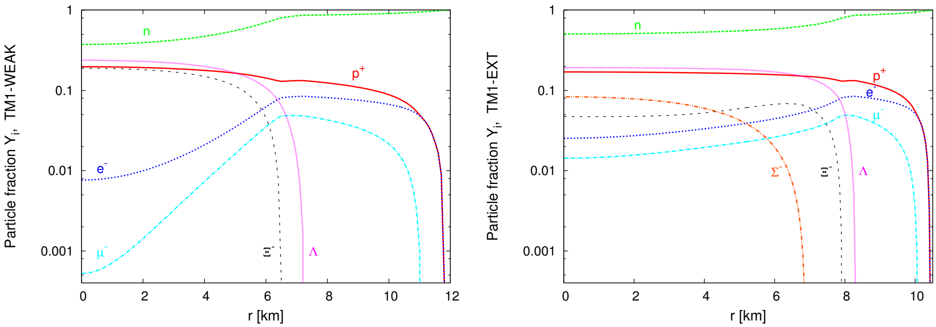
(a) The mass *vs.* total strangeness content.



(b) The radius *vs.* total strangeness content.

Fig. 2. The mass and radius as a function of the total strangeness content of system calculated for hyperon-rich neutron star matter. Calculations were done for different values of parameter $\Lambda_{\rm V}$. Black dots represent the maximum mass configurations for considered models.

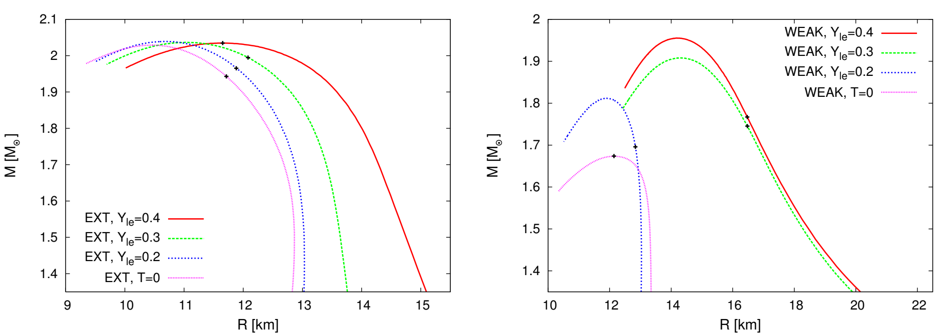
$\Lambda_{\rm V}$ is only visible for the nonlinear extended model. In the right panel, the radius–total strangeness content relation is given. The parameter $\Lambda_{\rm V}$ changes the values of radii only in the case of TM1-extended model. The specific value of the strangeness content δ_S determines the composition of neutron star matter and changes concentrations of particular constituents of the matter. Figure 3 illustrates radial dependence of particle concentrations calculated for the considered models for the maximum mass configurations. Population of hyperons is reduced in the case of the extended model. Characteristic feature of this model is the presence of Σ hyperons in the core of a neutron star. This type of hyperons are suppressed in the neutron star matter for the TM1-weak model.



(a) The TM1-weak model. (b) The extended nonlinear model.

Fig. 3. The radial dependence of the particle fractions $Y_i = n_i/n_b$ obtained for the maximum mass configurations. Calculations have been done for parameter $\Lambda_{\mathrm{V}} = 0.0165$ in the case of the TM1-weak and extended nonlinear models.

Various scenarios of neutron star evolution, beginning at the hot neutrino opaque proto-neutron star ($Y_{le} = 0.4$), through a process of deleptonization, to the cold neutron star ($T = 0$), are presented in Fig. 4. In the case of extended nonlinear model (Fig. 4 (a)), black points illustrate the evolutionary path of a proto-neutron star starting from the maximum mass configuration. This chosen configuration characterized by a specified baryon number, evolves into a stable cold neutron star with the mass, that is less than the maximum mass. Similar analysis can be done for the TM1-weak model (Fig. 4 (b)). Black dots represent the evolution of a neutron star with the fixed baryon number. In this case, for the early phase of neutron star evolution, there is a range of masses that are unstable.



(a) The extended nonlinear model. (b) The TM1-weak model.

Fig. 4. The M–R relations calculated for different stages of neutron star evolution for the value of parameter $\Lambda_{\mathrm{V}} = 0.0165$ in the case of hyperon-rich matter. Black points illustrate the evolutionary path of chosen neutron star configurations.

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