The maximum neutron star mass and the role of the enhanced vector meson interactions

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Abstract

The equation of state which is crucial for the structure and composition of a star has been obtained on the basis of the relativistic field theoretical model which in the minimal form comprises baryons, leptons and σ, ω and ρ meson fields. Scalar (σ^*) and vector (ϕ) mesons have been introduced to simulate hyperon – hyperon interaction. The considered model has been extended by couplings between vector mesons: $\omega-\rho$, $\omega-\phi$ and $\rho-\phi$. These additional nonlinear vector meson terms influence properties of neutron star matter and through this lead to the modification of the structure and properties of a hyperon star. The mixed vector meson interactions are very effective in describing asymmetric nuclear matter as they provide modification of the density dependence of the symmetry energy. For sufficiently high density this model describes the additional repulsion in hyperon interactions. This has remarkable consequences for the stiffening of the equation of state.

Motivation

- Observations of the binary millisecond pulsars J1614-2230 [1] and J0348+0432 [2] have led to the precise estimation of neutron star masses: $(1.97\pm0.04)M_\odot$ and $(2.01\pm0.04)M_\odot$.
- This shifts the maximum neutron star mass M_{max} towards rather high values and rules out most of the EoSs with hyperons - the models which involve exotic particles predict maximum neutron star masses well below $2M_\odot$.
- There is a need to analyze whether it is possible to construct an EoS of neutron star matter which gives adequately high maximum mass despite including hyperons.

Introduction

Constituents of the models

- Standard TM1 model: nucleons (n, p), leptons (e^-, μ^-), scalar meson σ and vector mesons ω_μ and ρ^a_μ
- TM1-weak model: hyperons (Λ, Σ, Ξ) and mesons (scalar σ^* and vector ϕ_μ) included in the minimal fashion, $\omega-\rho$ mixing
- Extended nonlinear model: additional $\omega-\phi$ and $\rho-\phi$ mixing

Conclusions

- In the case when hyperons are included additional repulse in the system is indispensable
- The model with the extended vector - meson sector leads to EoS that is much stiffer than the one constructed on the basis on the minimal model (TM1-weak)
- U^N_Σ potential change does not result in a sufficiently high stiffening of the EoS, however, modifies the chemical composition of the stars
- A characteristic feature of the model is the change of the effective baryon and meson masses with particular emphasis on the effective ϕ meson mass. There is a range of density for which the effective ϕ meson mass decreases.

References

[1] P. Demorest et al., *Nature* **467**, 1081 (2010)
[2] J. Antoniadis et al., *Science* **340**, 6131 (2013)
[3] R. B. Wiringa et al., *PRC* **38**, 1010 (1988)
[4] I. Bednarek et al., *J. Phys. G* **36**, 095201 (2009)
[5] Y. Sugahara et al., *Prog. Theor. Phys.* **92**, 803 (1994)
[6] G. A. Lalazissis et al., *PRC* **55**, 540 (1997)
[7] B. Todd-Rutel et al., *PRL* **95**, 122501 (2005)

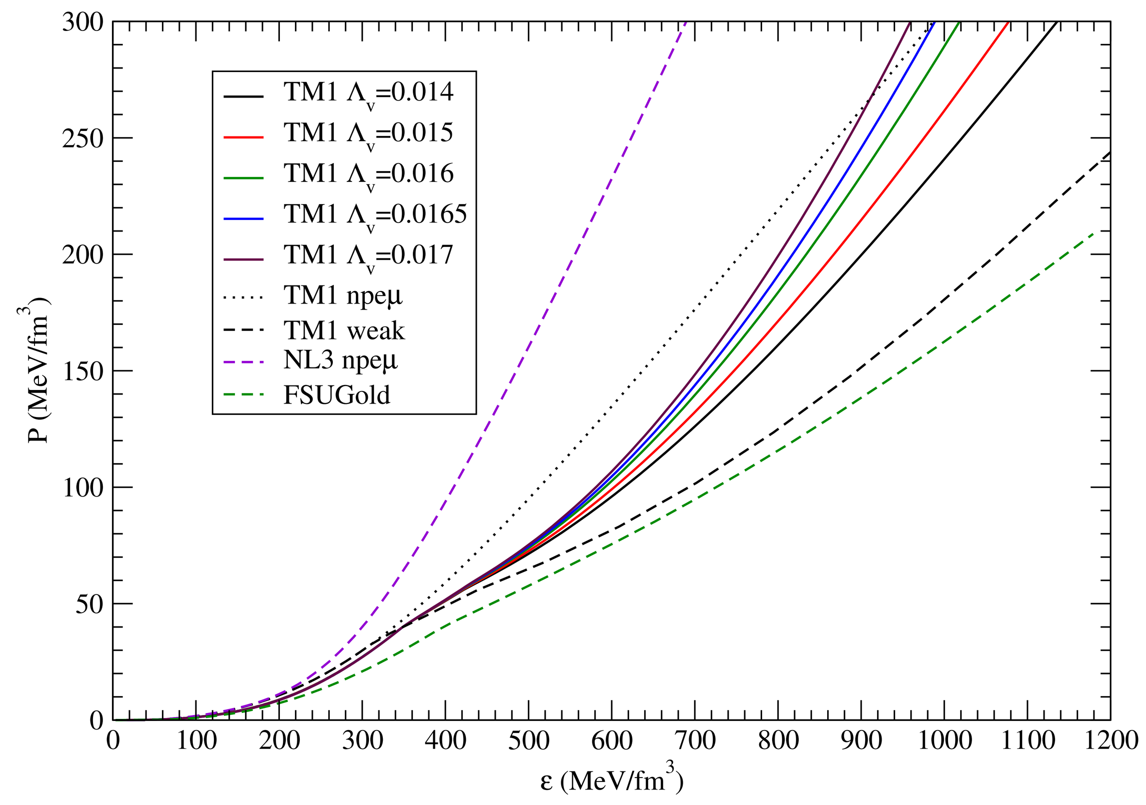
The model

The dynamics of the model considered is determined by a Lagrangian density [4] which embodies contributions from baryons, mesons and leptons:

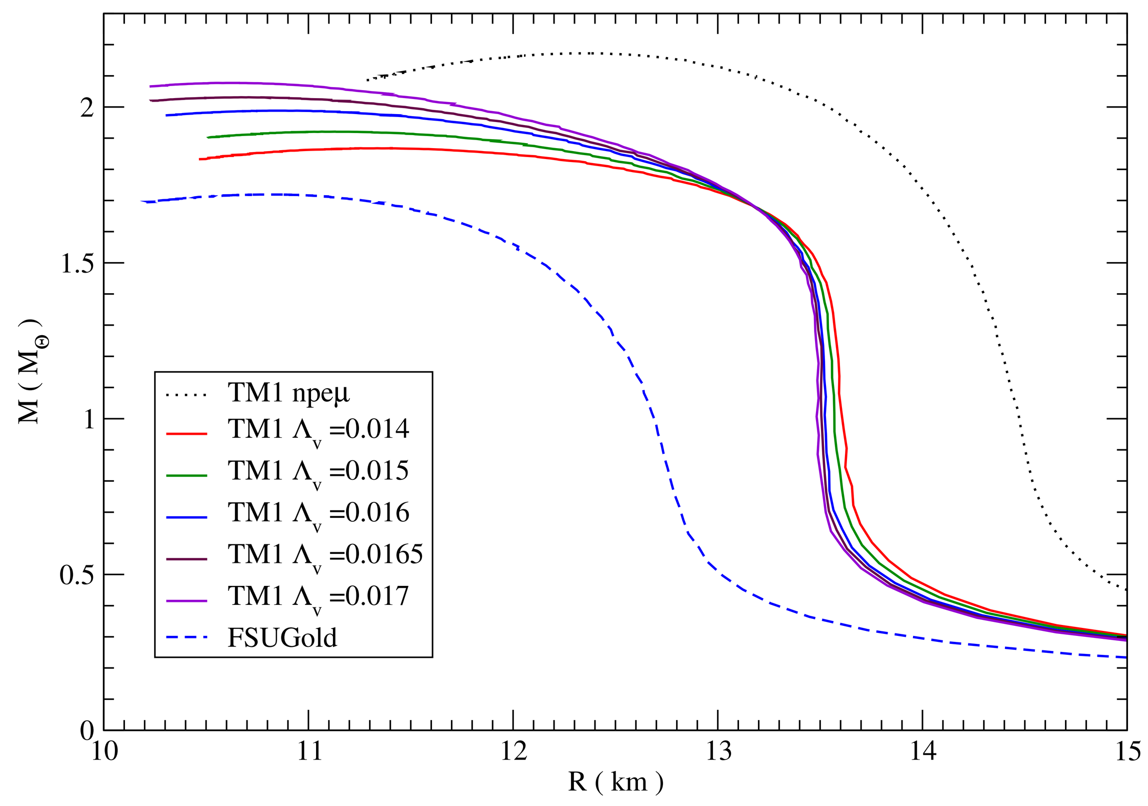
$$\begin{aligned}\mathcal{L} = & \sum_B \overline{\psi}_B\left(\gamma^\mu iD_\mu - m_{eff,B}\right)\psi_B + \frac{1}{2}\partial^\mu\sigma\partial_\mu\sigma - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{3}g_3\sigma^3 - \frac{1}{4}g_4\sigma^4 + \frac{1}{2}\partial^\mu\sigma^*\partial_\mu\sigma^* - \frac{1}{2}m_{\sigma^*}^2\sigma^{*2} + \\ & + \frac{1}{2}m_\omega^2(\omega^\mu\omega_\mu) + \frac{1}{2}m_\rho^2(\rho^{\mu a}\rho^a_\mu) + \frac{1}{2}m_\phi^2(\phi^\mu\phi_\mu) - \frac{1}{4}\Omega^{\mu\nu}\Omega_{\mu\nu} - \frac{1}{4}R^{\mu\nu a}R^a_{\mu\nu} - \frac{1}{4}\Phi^{\mu\nu}\Phi_{\mu\nu} + \frac{1}{4}c_3(\omega^\mu\omega_\mu)^2 + \\ & + \Lambda_V(g_{N\omega}g_{N\rho})^2(\omega^\mu\omega_\mu)(\rho^{\mu a}\rho^a_\mu) + \frac{1}{4}c_3(\rho^{\mu a}\rho^a_\mu)^2 + \frac{1}{4}\left(\frac{1}{2}c_3 + \Lambda_V(g_{N\omega}g_{N\rho})^2\right)(\phi^\mu\phi_\mu)^2 + \\ & + \frac{1}{2}\left(\frac{3}{2}c_3 - \Lambda_V(g_{N\omega}g_{N\rho})^2\right)(\omega^\mu\omega_\mu + \rho^{\mu a}\rho^a_\mu)(\phi^\mu\phi_\mu) + \sum_{l=e,\mu}\overline{\psi}_l(i\gamma^\mu\partial_\mu - m_l)\psi_l,\end{aligned}$$

where the covariant derivative equals $D_\mu = \partial_\mu + ig_{B\omega}\omega_\mu + ig_{B\phi}\phi_\mu + ig_{B\rho}\mathbf{I}_B\boldsymbol{\rho}_\mu$, $\mathbf{I}_B$ denotes isospin of baryon B. The baryon effective mass is defined as follows $m_{eff,B} = m_B - g_{B\sigma}\sigma - g_{B\sigma^*}\sigma^*$, while $\Omega_{\mu\nu}$, $\mathbf{R}_{\mu\nu}$, and $\Phi_{\mu\nu}$ are the field tensors of the ω, ρ, and ϕ mesons. The basic parameters of the model is TM1 parameter set [5]. In the non-strange sector the model is extended by the $\omega-\rho$ meson coupling, the strength of this coupling is given by the parameter Λ_V. All calculations have been done within the RMF approximation.

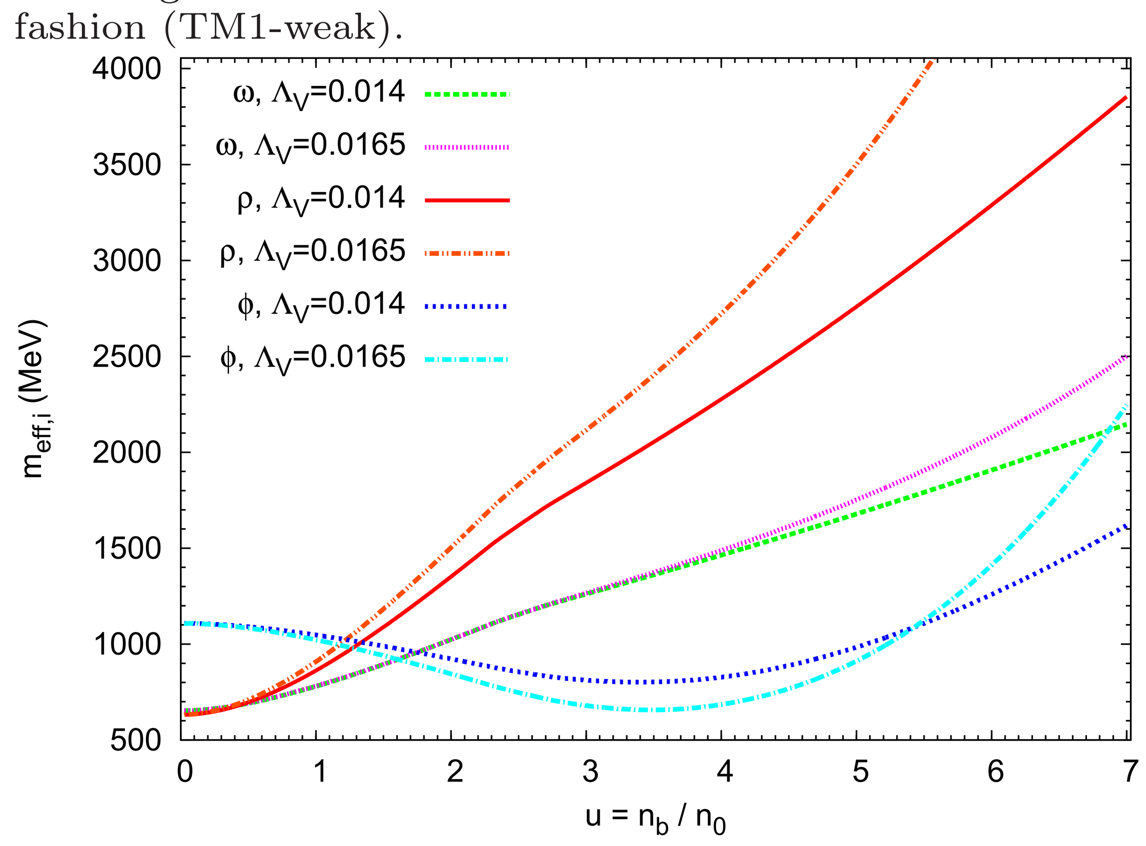
Results



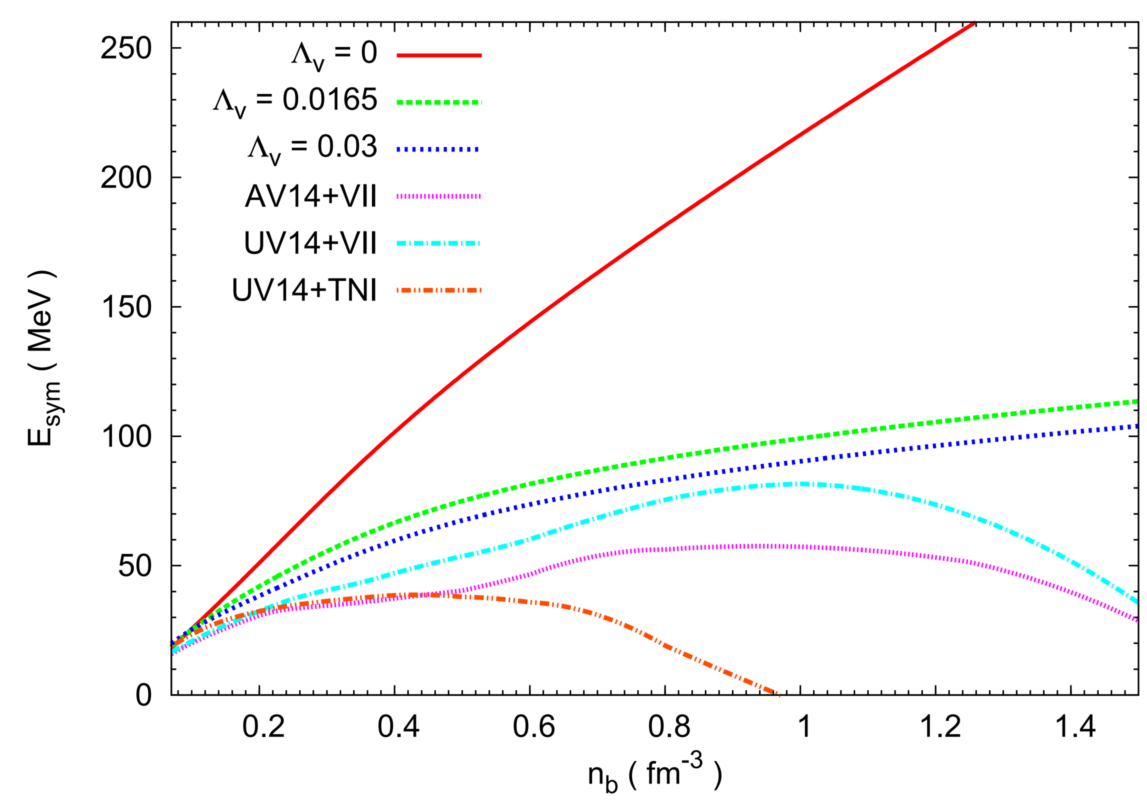
The EoS calculated for the nonlinear model for different values of the coupling constant Λ_V. The results have been obtained for the non-strange matter for TM1 [5], NL3 [6] and FSUGold [7] parameter sets. Black dotted line represents the case of the standard TM1 model extended by the inclusion of strange mesons which have been introduced in a minimal fashion (TM1-weak).



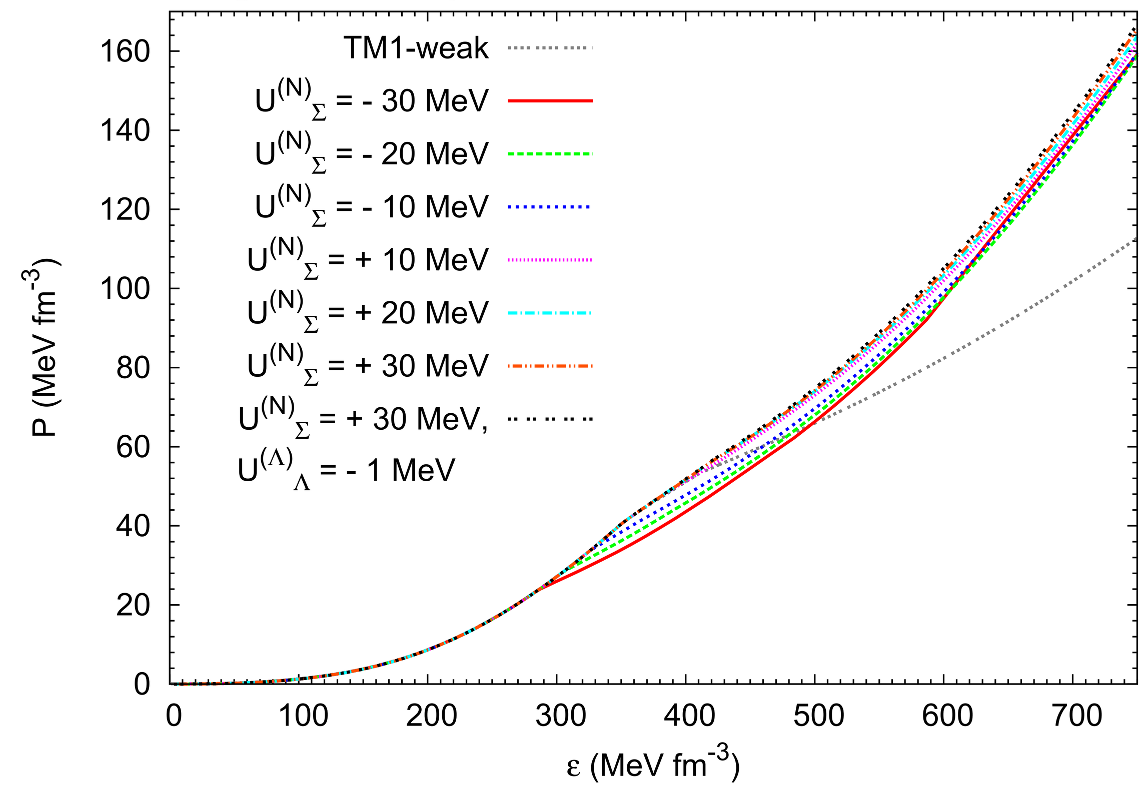
The mass–radius relations calculated for the extended nonlinear model for different values of parameter Λ_V. The results have been supplemented with the TM1 and FSUGold [7] parameterisations in the case when the matter of the neutron star comprises only nucleons.



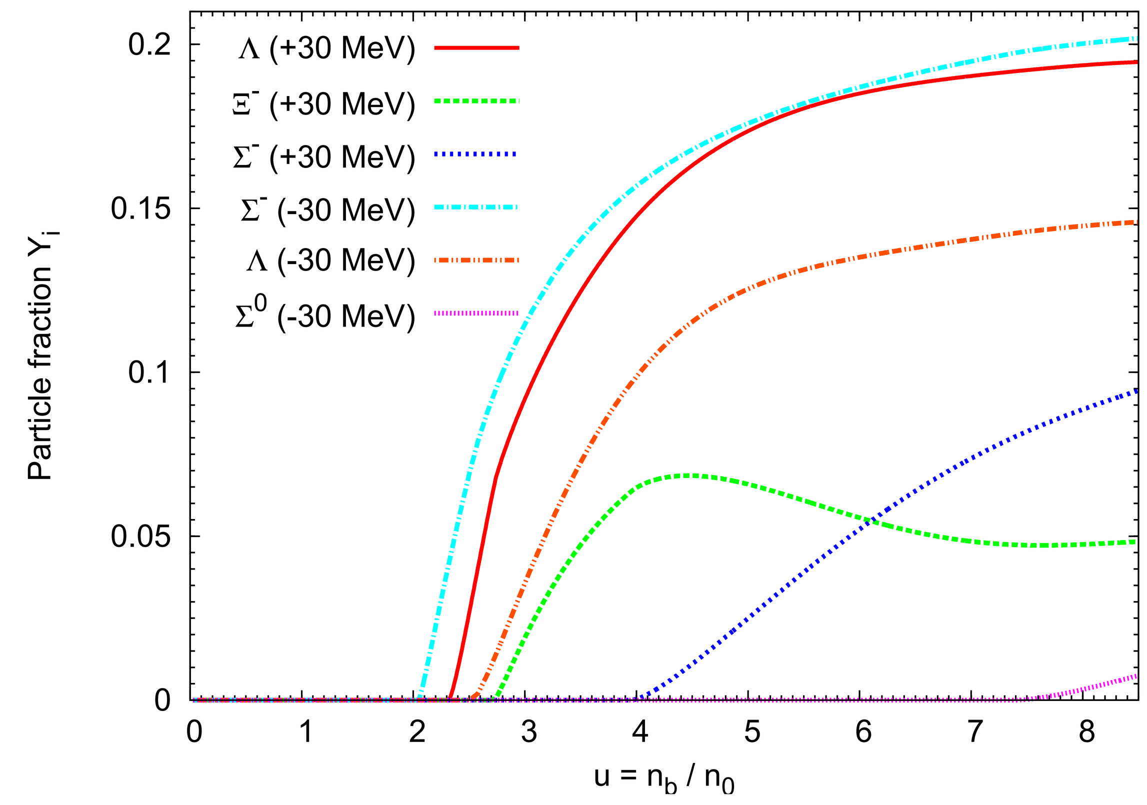
The effective meson masses as a function of baryon number density calculated for the extended nonlinear model, for $\Lambda_V = 0.014$ and $\Lambda_V = 0.0165$. In the case of ω and ρ mesons the increase of Λ_V parameter results in their higher effective masses. While for the effective mass of the ϕ meson there exists a range of density where its effective mass decreases.



The density dependence of symmetry energy calculated for different values of parameter Λ_V and compared with the results obtained for the AV14+VII, UV14+VII and UV14+TNI models [3]. The inclusion of Λ_V parameter softens the symmetry energy and its density dependence resembles that obtained for the realistic nuclear models.



The pressure vs density calculated for different values of the U^N_Σ potential (attractive and repulsive), the very weak $U^{(\Lambda)}_\Lambda$ case has been icluded. In the case of the extended nonlinear model the higher value of the repulsive $U^{(N)}_\Sigma$ potential leads to the stiffer EoS.



Relative concentrations of hyperons calculated for the extended nonlinear model for the repulsive and attractive $U^{(N)}_\Sigma$ potential. In the case of the repulsive potential the first hyperon that appears is Λ and it is followed by Ξ^- and Σ^-. For attractive potential hyperons appear in the following order: Σ^-, Λ and Σ^0