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

Monika Pieńkos
University of Silesia, Uniwersytecka 4, 40-007 Katowice Poland, m pienkos@us.edu.pl

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 \( \rho \) meson fields. Scalar (\( \sigma \)) and vector (\( \phi \)) mesons have been introduced to simulate hyperon – hyperon interaction. The considered model has been extended by couplings between vector mesons: \( \omega \) – \( \rho \), \( \phi \) – \( \rho \) and \( \phi \) – \( \phi \). These additional nonlinear vector meson vector mesons term 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 the model exhibits the minimal 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 ± 0.04)\( M_{\odot} \) and (2.01 ± 0.04)\( M_{\odot} \).
• This shifts the maximum neutron star mass \( M_{\text{max}} \) towards higher values and rules out most of the EoSs with hyperons - the models which involve exotic particles predict maximum neutron star masses well below 2\( M_{\odot} \).
• 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 (\( e^- , \mu^- \)), scalar mesons \( \sigma \) and vector \( \rho \) and \( \phi \) mesons.
• TM1-weak model: hyperons (\( \Lambda, \Sigma, \Xi \)) and mesons (scalar \( \sigma \) and vector \( \phi \)) included in the minimal fashion, \( \omega \) – \( \rho \) mixing
• Extended nonlinear model: additional \( \omega \) – \( \sigma \) and \( \phi \) – \( \phi \) mixing

Conclusions
• In the case when hyperons are included additional repulsive in the system is indispensable.
• The model with the extended vector - meson sector leads to EoS of which is such stiffer than the one constructed on the basis on the minimal model (TM1-weak).
• \( U_{\phi}^2 \) 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 \( \phi \) meson mass. There is a range of density for which the effective \( \phi \) meson mass decreases.

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

\[
\mathcal{L} = \sum_{\mu} \left( \frac{\partial}{\partial t} \psi_{\mu} D_{\mu} \psi_{\mu} - m_{\mu f f} \psi_{\mu} \psi_{\mu} \right) + \frac{1}{2} \partial^2 \sigma \partial^2 \sigma - \frac{1}{2} \omega^2 \sigma^2 - \frac{1}{2} \rho^2 \phi^2 - \frac{1}{2} \omega^2 \omega^2 - \frac{1}{2} \rho^2 \phi^2 - \frac{1}{2} \omega^2 \phi^2 + \frac{1}{2} \partial^a \omega \partial^b \omega + \frac{1}{2} \partial^a \rho \partial^b \rho + \frac{1}{2} \partial^a \phi \partial^b \phi + \frac{1}{4} \partial \phi \partial \omega \partial \omega \partial \omega + \frac{1}{4} \partial \phi \partial \rho \partial \rho \partial \rho + \frac{1}{4} \partial \phi \partial \phi \partial \phi \partial \phi
\]

where the covariant derivative equals

\[
D \mu \psi_{\mu} = \partial \mu \psi_{\mu} - i \gamma^\mu \left( \partial \mu \right) \psi_{\mu} \psi_{\mu}
\]

Results
The EoS calculated for the nonlinear model for different values of the coupling constant \( \Lambda_V \). 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 \( \Lambda_V \). 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 density dependence of symmetry energy calculated for different values of parameter \( \Lambda_V \) and compared with the results obtained for the AV14+VII, UV14+VII and UV14+TM1 models [5]. The inclusion of \( \Lambda_V \) parameter softens the symmetry energy and its density dependence resembles that obtained for the realistic nuclear models.

References