https://doi.org/10.1051/epjconf/202227109001

Neutron stars and the hyperon puzzle

Isaac Vidaña[1,*]

[1]Istituto Nazionale di Fisica Nucleare, Sezione di Catania. Dipartimento di Fisica e Astronomia "Ettore Majorana", Università di Catania, Via Santa Sofia 64, I-95123 Catania, Italy

Abstract.
In this work we shortly review the so-called "hyperon puzzle", *i.e.,* the problem of the strong softening of the equation of state of dense matter induced by the presence of hyperons which leads to maximum masses of neutron stars incompatible with the recent observations of $\sim 2\,M_\odot$ millisecond pulsars. In particular, we briefly go through some of the possible solutions that have been proposed to tackle this still open problem.

1 Introduction

Neutron stars are one of the possible stellar compact remnants resulting from the gravitational collapse of massive stars during a Type-II, Ib or Ic supernova event. With masses of the order of $1-2M_\odot$, where $M_\odot \simeq 2\times10^{33}$g is the mass of the Sun, radii of about $10-12$ km, and central densities in the range of $4-8$ times the normal nuclear matter saturation density, $\epsilon_0 \sim 2.7\times10^{14}$ g/cm^3 ($\rho_0 \sim 0.16$ fm^{-3}), neutron stars are most likely among the densest objects in the Universe [1]. These objects are excellent laboratories to test our present understanding of the theory of strongly interacting matter under extreme conditions, offering an interesting interplay between nuclear physics of dense matter and astrophysical observations. Enormous theoretical advances have been done in understanding the extreme and unique properties (magnetic fields, rotational frequencies, gravitational fields, surface temperatures) of these exotic objects. Major advances have been also achieved in their observation. Particularly important has been the observation in 2017 of the first gravitational wave signal from the merger of two neutron stars [2], inaugurating a new era in the observation of these objects.

Nowadays it is still an open question what is the true internal composition of neutron stars. Neutron stars has been traditionally modeled as a uniform fluid of neutron-rich nuclear matter in equilibrium with respect to weak interaction processes (β-stable matter). However, due to the large values reached by the density, new hadronic degrees of freedom are expected to appear in neutron star interiors in addition to nucleons. Hyperons, baryons with a strangeness content, are an example of these new degrees of freedom. Contrary to terrestrial conditions, where hyperons are unstable and decay into nucleons through weak interactions, the equilibrium conditions in neutron stars can make the inverse process happen. Hyperons may appear in the inner cores of neutron stars at densities around $(2-3)\times\rho_0$, leading their onset to a softening of the equation of state (EoS) and consequently to a reduction of the neutron star mass and, particularly, of its maximum value to values smaller than current observations of $\sim 2\,M_\odot$ [3–5]. The difficulty in reconciling the presence of hyperons in the neutron stars

*e-mail: isaac.vidana@ct.infn.it

 https://doi.org/10.1051/epjconf/202227109001

interior with current mass observations is nowadays one of the most important open problem in nuclear astrophysics. This problem, known in the literature as the "hyperon puzzle", is a subject of current intensive research.

In the next sections we discuss in some detail the hyperon puzzle, and briefly present some of the possible solutions to this problem that have been proposed in the recent years. The manuscript is finished with a brief summary given at the end.

2 The hyperon puzzle

The presence of hyperons in neutron stars was considered for the first time in the pioneering work of Ambartsumyan and Saakyan in 1960 [6]. Since then, their effects on the properties of these objects have been studied by many authors using either phenomenological [7, 8] or microscopic [9–13] approaches to the EoS of neutron star matter. Phenomenological approaches, either relativistic or non-relativistic, are based on effective density-dependent interactions which typically contain a certain number of parameters adjusted to reproduce nuclear and hypernuclear observables, and neutron star properties. Relativistic mean field (RMF) models [7] and models based on the Skyrme-type interactions [8] are among the most commonly used ones. Microscopic approaches, on the other hand, are based on realistic two- and three-body baryon interactions that describe the scattering data in free space. These realistic interactions have been mainly constructed within the framework of a meson-exchange theory [14, 15], although recently a new approach based on chiral perturbation theory has emerged as a powerful tool [16]. In order to obtain the EoS one has to solve then a very complicated many-body problem [17]. A great difficulty of this problem lies in the treatment of the repulsive core, which dominates the short-range behavior of the interaction. Although many different microscopic many-body methods have been extensively used to study nuclear matter, very few of these have been extended to hypernuclear sector. To our knowledge, these many-body methods include the Brueckner–Hartree–Fock (BHF) approximation [9] of the Brueckner–Bethe–Goldstone theory, the Hartree–Fock theory based on the soft $V_{low\,k}$ interactions [10] and the Dirac–Brueckner–Hartree–Fock theory [11, 12]. Very recently the Auxiliary Field Diffusion Monte Carlo method [13] was also extended to the hyperonic sector.

All these approaches agree that hyperons may appear in the inner core of neutron stars at densities around $\sim (2-3) \times \rho_0$. At such densities, the nucleon chemical potential is large enough to make the conversion of nucleons into hyperons energetically favorable. This conversion relieves the Fermi pressure exerted by the nucleons and makes the EoS softer. This is a common feature of all models including hyperons, and it is illustrated in panel (a) of Fig. 1 for the particular example of the GM3 parametrization of the Glendenning–Moszkowski RMF model (see Ref. [7]) with (red dashed line) and without (black solid line) hyperons. As a consequence (see panel (b)) the masses of the stars with central densities beyond the onset density of the hyperons are lower and the maximum mass of hyperonic stars is substantially reduced.

Although the presence of hyperons in neutron stars seems to be energetically unavoidable, the strong softening of the EoS associated with the onset of hyperons (notably in microscopic models) leads to maximum masses not compatible with observations. The discrepancy between the theory and observations became more dramatic after the recent measurements of $\sim 2\,M_\odot$ millisecond pulsars [3–5] which rule out most of all currently proposed EoS with hyperons.

To solve this problem it is needed a mechanism that could provide the additional repulsion that makes the EoS stiffer at high densities and, therefore, the maximum mass compatible with the current observational limits. Four of the possible mechanisms that could provide

 https://doi.org/10.1051/epjconf/202227109001

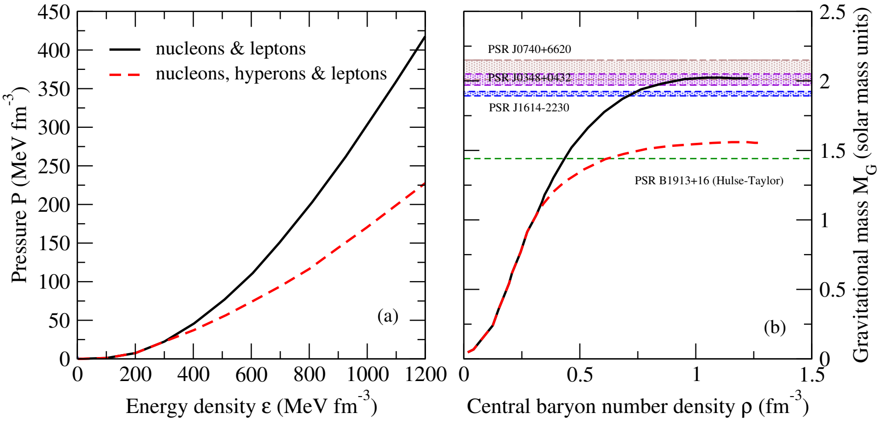

Figure 1. Illustration of the effect of the presence of hyperons on the EoS (panel (a)) and mass of a neutron star (panel (b)). The GM3 parametrization of the Glendenning–Moszkowski RMF model (see Ref. [7]) with (red dashed line) and without (black solid line) hyperons has been considered as an example. The bands show the observational masses and their corresponding errors of the PSR B1913+16 (Hulse–Taylor) [18] pulsar, and the millisecond pulsars PSR J1614-2230 [3], PSR J0348+0432 [4] and PSR J0740+6620 [5].

such additional repulsion are: (i) more repulsive hyperon-hyperon interactions in relativistic density functional methods driven by either repulsive vector mesons exchanges [19–22] or less-attractive scalar σ meson exchange [23], (ii) repulsive hyperonic three-body forces [24–28, 30], (iii) phase transition to deconfined quark matter at densities below the hyperon threshold [34–38] and (iv) appearance of other hadronic degrees of freedom, such as the Δ isobar [41] or meson condensates [42–47] that shift the onset of hyperons to larger densities. Each one of these possible solutions is briefly reviewed in the following sections.

3 Hyperon-hyperon repulsion

This solution, which has been mainly explored in the context of RMF models (see *e.g.,* Refs. [19–23]), relies on the well-known fact that in meson-exchange models of nuclear forces vector mesons generate repulsion at short distances while σ-meson is responsible for intermediate range attraction. If the interaction of hyperons with vector mesons is repulsive enough or the attraction driven by the σ-meson is weak enough then the neutron star matter EoS could be sufficiently stiff to explain the current pulsar mass observations. However, the modifications of the strength of meson exchanges must be consistent with the hypernuclear data which requires, at least, the ΛN interaction to be attractive and suitable tuned to the hypernuclear data [39]. Such tuning is not required if the repulsive vector meson interactions acts only among the hyperons through the exchange of the strange ϕ vector meson (which couples only to hyperons). In this way, the onset of hyperons would be shifted to higher densities and neutron stars with maximum masses larger than $2M_\odot$ and a significant hyperon fraction could be successfully obtained. It is also possible to tune the interactions of non-strange mesons to accommodate the hypernuclear data and astrophysical constraints on maximum masses of neutron stars in the framework of relativistic density functional theories (for such an approach see *e.g.* Ref. [23]). For more details the interested reader is referred to the original recent work quoted above.

4 Hyperonic three-body forces

It is well known that the three-nucleon forces in the nuclear Hamiltonian are fundamental ingredients that are needed to reproduce properly the properties of few-nucleon systems as well as the empirical saturation point of symmetric nuclear matter in non-relativistic many-body approaches. Therefore, it seems natural to suggest that three-body forces involving one or more hyperons (*i.e.,* NNY, NYY and YYY) could provide additional repulsion at high densities (already established in the case of three-nucleon forces) that can solve the hyperon puzzle. Indeed if three-body forces involving hyperons are repulsive enough they can make the EoS stiffer at high densities and, therefore, make the maximum mass of the star compatible with the recent observations. This idea was suggested even before the observation of neutron stars with $\sim 2M_{\odot}$ (see *e.g.,* Ref. [24]), and it has been explored by a number of authors in the last years [25–28, 30]. However, no general consensus has been reached regarding the role played by the hyperonic three-body forces in solving the hyperon puzzle. The authors of Refs. [24, 26] found that the inclusion of hyperonic three-body forces is sufficient to obtain hyperon stars with masses of the order of $2M_{\odot}$, whereas in Ref. [25] it was fund that the largest maximum mass attainable within their model is $1.6M_{\odot}$. The authors of [27] concluded that, with the model they considered, the presence of hyperons in the core of neutron stars could not be satisfactory established and, conse- quently, according to these authors, there is no clear incompatibility with astrophysical observations when Λs are included. However, one should note, that the presence of protons, necessary to establish the correct β-equilibrium inside neutron stars and thus a proper treatment of neutron star matter EoS, was neglected in their calculation. On the other hand, the results of Ref. [28] showed that the inclusion of a NNΛ force, derived by the Jülich–Bonn–Munich group within the framework of chiral effective field theory (χEFT) at next-to-next-to-leading order, leads to an EoS stiff enough such that the resulting hyperon star maximum mass is compatible with the largest masses currently observed. Using a perturbative many-body approach these authors calculated also the separation energy of the Λ hyperon in some hypernuclei finding that the agreement with the experimental data improves for the heavier ones when the effect of a repulsive NNΛ force of the order of $\sim$ 10 MeV at saturarion is taken into account. Recently, Friedman and Gal [29] found that a repulsive contribution of about 14 MeV to the Λ-nucleus potential in symmetric matter at saturation could potentially solve the hyperon puzzle. This is in complete agreement with the results of Ref. [28] just mentioned. Finally, the recent microscopic ab-inito calculations of Ref. [30] of the Λ hyperon properties in symmetric nuclear matter and pure neutron matter, performed with NΛ and NNΛ potentials derived within the framework of χEFT, indicate that the appearance of hyperons in neutron stars could be energetically unfavorable. However, a complete calculation under conditions of chemical equilibrium found in neutron stars made with χEFT is still missing. To conclude, although it seems that hyperonic three-body forces offer an interesting microscopic solution to the hyperon puzzle, however the uncertainties involved in the physics of hyperonic three-body forces are too large at the moment to make a definite conclusion possible.

5 Phase transition to deconfined quark matter

Several authors have suggested that an early phase transition from hadronic mater to deconfined quark matter at densities below the hyperon threshold could provide a solution to the hyperon puzzle. Therefore, massive neutron stars could actually be hybrid stars with a stiff quark matter core. The question that arises then is whether quarks can provide sufficient repulsion to produce a $2M_{\odot}$ neutron star. To yield maximum masses larger than $2M_{\odot}$, quark matter should have two important and necessary features: (i) a significant overall quark-quark repulsion to maintain stiff EoS, for example, in vector channels and (ii) a strong enough attraction in certain channels which leads to color superconductivity needed to make the deconfined quark matter phase energetically favorable over the hadronic one [40]. Several models of hybrid stars with the necessary properties to generate $2M_\odot$ neutron stars have been proposed [31–38]. Conversely, the observation of $2M_\odot$ neutron stars may also helped to impose important constraints on the models of hybrid and strange stars with a quark matter core, and improve our present understanding of the hadron-quark phase transition.

6 Δ isobar and kaon condensation in neutron stars

An alternative way to circumvent the hyperon puzzle is to invoke the appearance of other hadronic degrees of freedom such as for instance the Δ isobar or meson condensates that shift the onset of hyperons to higher densities.

The Δ isobar is often neglected in the studies of neutron stars because its threshold density was found to be higher than the typical densities prevalent in cores of neutron stars. Nevertheless, it has been recently shown by Drago *et al.,* [41] that the onset of the Δ depends crucially on the density-dependence of the slope of the nuclear symmetry energy, *i. e.*, the parameter $L = 3\rho_0(\partial E_{sym}(\rho)/\partial\rho)_{\rho_0}$. By using a state-of-the-art EoS and recent experimental constraints on L, these authors showed that the Δ isobar could actually appear before the hyperons in neutron star interiors. However, they found also that, as soon as the Δ is present the EoS, as in the case of hyperons, becomes considerably softer and, consequently, the maximum mass is reduced to values below the current observational limit. Thus, the hyperon puzzle is effectively replaced with the so-called Δ puzzle.

The possible existence of a Bose–Einstein condensate of negative kaons in the inner core of neutron stars has also been extensively considered in the literature (see *e.g.,* [42–47] and references therein). As the density of stellar matter increases, the K^- chemical potential, μ_{K^-}, is lowered by the attractive vector meson field originating from dense nucleonic mater. When μ_{K^-} becomes smaller than the electron chemical potential μ_e the process $e^- \to K^- + \nu_e$ becomes energetically possible. The critical density for this process was calculated to be in the range $2.5 - 5\rho_0$ [45, 46]. However, as in the case of the Δ, the appearance of the kaon condensation induces also a strong softening of the EoS and consequently leads to a reduction of the maximum mass to values below the current observational limits. The interested reader is referred to the original work on this subject [42–47] for a comprehensive description of the implications of kaon condensation on the structure and evolution of neutron stars.

7 Summary

In this paper we briefly reviewed the so-called "hyperon puzzle", *i.e.,* the problem of the strong softening of the EoS of dense matter due to the appearance of hyperons which leads to maximum masses of compact stars that are not compatible with the recent observations of $\sim 2M_\odot$ millisecond pulsars. We have discussed four of the different solutions that have been proposed to tackle this problem: (i) more repulsion in hyperon-hyperon interactions within the density functional theories of hypernuclear matter in the vector and/or scalar mesons exchange channels; (ii) repulsive hyperonic three-body forces in the ab initio microscopic calculations, (iii) a phase transition to deconfined quark matter at densities below the hyperon threshold, and (iv) the appearance of other hadronic degrees of freedom that could shift the onset of hyperons to larger densities.

Acknowledgements

The author is very grateful to the organizers of HYP2022 for their invitation. This work has received funding from the Helmholtz Institute Mainz and the European Union's Horizon 2020 research and innovation programme under grant agreement No. 824093.

References

[1] S. L. Shapiro and S. A. Teukolsky, *Black Holes, White Dwarf and Neutron Stars* (Wiley, New York) 1983; N. K. Glendenning, *Compact Stars: Nuclear Physics, Particle Physics and General Relativity*, 2nd edition (Springer, Berlin) 2000; P. Haensel, A. Y. Potekhin and D. G. Yakovlev, *Neutron Stars 1: Equation of State and Structure, Astrophysics and Space Science Library Series*, Vol. **326** (Springer, New York) 2007

[2] B. P. Abbott *et al.* (LIGO Scientific Collaboration and Virgo Collaboration), Phys. Rev. Lett. **116**, 061102

[3] P. Demorest *et al.,* Nature **467**, 1081 (2010); Z. Arzoumanian *et al.,* Astro. Phys. J. Suppl. Ser. **235** (2), 37 (2018)

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

[5] H. T. Cromartie *et al.,* Nature Astronomy **10**, 1038 (2019); E. Fonseca *et al.,* Astro. Phys. J. Lett. **915**, L12 (2021)

[6] V. A. Ambartsumyan and G. S. Saakyan, Sov. Astron. **4**, 187 (1960)

[7] N. K. Glendenning, Phys. Lett. B **114**, 392 (1982); N. K. Glendenning, Astrophys. J. **293**, 470 (1985); N. K. Glendenning, Z. Phys. A **326**, 57 (1987); N. K. Glendening and S. A. Moszkowski, Phys. Rev. Lett. **67**, 2414 (1991); F. Weber and M. K. Weigel, Nucl. Phys. A **505**, 779 (1989). R. Knorren, M. Prakash and P. J. Ellis, Phys. Rev. C **52**, 3470 (1995); J. Schaffner and I. Mishustin, Phys. Rev. C **53**, 1416 (1996); H. Huber, F. Weber, M. K. Weigel and Ch. Schaab, Int. J. Mod. Phys. E **7**, 310 (1998)

[8] S. Balberg and A. Gal, Nucl. Phys. A **625**, 435 (1997); S. Balberg, I. Lichtenstadt and G. B. Cook, Astrophys. J. Suppl. Ser. **121**, 515 (1999). D. E. Lanskoy and Y. Yamamoto, Phys. Rev. C **55**, 2330 (1997); T. Y. Tretyakova and D. E. Lanskoy, Eur. Phys. J. A **5**, 391 (1999); J. Cugnon, A. Lejeune and H.-J. Schulze, Phys. Rev. C **62**, 064308 (2000); I. Vidaña, A. Polls, A. Ramos and H.-J. Schulze, Phys. Rev. C **64**, 044301 (2001); X.-R. Zhou , H.-J. Schulze, H. Sagawa, C.-X. Wu and E.-G. Zhao, Phys. Rev. C **76**, 034312 (2007); X.-R. Zhou, A. Polls, H.-J. Schulze and I. Vidaña, Phys. Rev. C **78**, 054306 (2008)

[9] H.-J. Schulze, M. Baldo, U. Lombardo, J. Cugnon and A. Lejeune, Phys. Lett. B **355** 21 (1995); H.-J. Schulze, M. Baldo, U. Lombardo, J. Cugnon and A. Lejeune, Phys. Rev. C **57**, 704 (1998); M. Baldo, G. F. Burgio and H.-J. Schulze, Phys. Rev. C **58**, 3688 (1998) M. Baldo, G. F. Burgio and H.-J. Schulze, Phys. Rev. C **61**, 055801 (2000); I. Vidaña, A. Polls, A. Ramos, M. Hjorth-Jensen and V. G. J. Stoks, Phys. Rev. C **61**, 025802 (2000); I. Vidaña, A. Polls, A. Ramos, L. Engvik and M. Hjorth-Jensen, Phys. Rev. C **62**, 035801 (2000); H-J. Schulze, A. Polls, A. Ramos and I. Vidaña, Phys. Rev. C **73**, 058801 (2006); H.-J. Shulze and T. Rijken, Phys. Rev. C **84**, 035801 (2011)

[10] H. Dapo, B.-J. Schaefer and J. Wambach, Phys. Rev. C **81**, 035803 (2010)

[11] F. Sammarruca, Phys. Rev. C **79** 034301 (2009)

[12] T. Katayama and K. Saito, arXiv:1410.7166 (2014); arXiv:1501.05419 (2015)

[13] D. Lonardoni, F. Pederiva and S. Gandolfi, Phys. Rev. C **89** 014314 (2014)

[14] P. M. M. Maessen, T. A. Rijken and J. J. de Swart, Phys. Rev. C **40**, 2226 (1989); Th. A. Rijken, V. G. J. Stoks and Y. Yamamoto, Phys. Rev. C **59**, 21 (1999); V. G. J. Stoks and

Th. Rijken, Phys. Rev C **59**, 3009 (1999); Th. A. Rijken, Phys. Rev. C **73**, 044007 (2006); Th. A. Rijken and Y. Yamamoto, Phys. Rev. C **73**, 044008 (2006)

[15] B. Holzenkamp, K. Holinde and J. Speth, Nucl. Phys. A **500**, 485 (1989); J. Haidenbauer and U.-G. Meissnes, Phys. Rev. C **72**, 044005 (2005)

[16] H. Polinder, J. Haidenbauer and U.- G. Meissner, Nucl. Phys. A **779**, 244 (2006); J. Haidenbauer, S. Petschauer, N. Kaiser, U.-G. Meissner, A. Nogga and W. Weise W 2013 Nucl. Phys. A **915** 24

[17] *Nuclear Methods and Nuclear Equation of State* (International Review of Nuclear Physics, Vol 8. Edited by Marcello Baldo. World Scientific Publishing Company 1999); H. Müther and A. Polls, Prog. Part. Nucl. Phys. **45**, 243 (2000)

[18] R. A. Hulse and J. H. Taylor, Astrophys. J. Lett. **195** L51 (1975)

[19] I. Bednarek, P. Haensel, J. L. Zdunik, M. Bejger and R. Mańka, Astron. and Astrophys. **543**, A157 (2012)

[20] S. Weissenborn, D. Chatterjee, and J. Schaffner–Bielich, Phys. Rev. C **85**, 065802 (2012)

[21] M. Oertel, C. Providência, F. Gulminelli and Ad. R. Raduta, J. Phys. G. **42** 075202 (2015)

[22] K. A. Maslov, E. E. Kolomeitsev and D. N. Voskresensky, Phys. Lett. B **748** 369 (2015)

[23] E. N. E. van Dalen, G. Colucci and A. Sedrakian, Phys. Lett. B **734**, 383 (2014)

[24] T. Takatsuka *et al.,* Eur. Phys. J. A **13**, 213 (2002); Prog. Theor. Phys. Suppl. **174**, 80 (2008)

[25] I. Vidaña, D. Logoteta, C. Providência, A. Polls and I. Bombaci, Eur. Phys. Lett. **94**, 11002 (2011)

[26] Y. Yamamoto, T. Furumoto, B. Yasutake and Th. A. Rijken, Phys. Rev. C **88** 022801 (2013); Phys. Rev. C **90** 045805 (2014)

[27] D. Lonardoni, A. Lovato, S. Gandolfi and F. Pederiva Phys. Rev. Lett. **114** 092301 (2015)

[28] D. Logoteta, I.Vidaña, and I. Bombaci, Eur. Phys. J. A **55**, 207 (2019)

[29] E. Friedman and A. Gal, arXiv:2204.02264

[30] D. Gerstung, N. Kaiser, and W. Weise, Eur. Phys. J. A **56**, 175 (2020)

[31] M. Baldo, M. Buballa, G. F. Burgio, F. Neumann, M. Oertel and H.-J. Schulze, Phys. Lett. B **562**, 153 (2003)

[32] M. Baldo, G. F. Burgio, P. Castorina, S. Plumari and Z. Zappalà, Phys. Rev. C **75**, 035804 (2007)

[33] A. Kurkela, P. Romatschke and A. Vuorinen, Phys. Rev. D **81**, 105021 (2010)

[34] F. Özel, D. Psaltis, S. Ransom, P. Demorest and M. Alford, Astrophys. J. Lett. **724** L199 (2010)

[35] S. Weissenborn, I. Sagert, G. Pagliara, M. Hempel and J. Schaeffner-Bielich, Astophys. J. Lett. **740** L14 (2011)

[36] T. Klähn, D. Blaschke and D. Lastowiecki, Phys. Rev. D **88** 085001 (2013)

[37] L. Bonanno and A. Sedrakian, Astron. and Astrophys. **539** 416 (2012)

[38] R. Lastowiecki, D. Blaschke, H. Grigorian and S. Typel Acta Phys. Polon. Suppl., **5** 535 (2012)

[39] O. Hashimoto and H. Tamura, Prog. Part. Nucl. Phys. **57** 564 (2006)

[40] J. L. Zdunik and P. Haensel, Astron. and Astrophys. **551** A61 (2013)

[41] A. Drago, A. Lavagno, G. Pagliara and D. Pigato, Phys. Rev. C **90**, 065809 (2014); EPJ Web Conf. **95**, 01011 (2015)

[42] D. B. Kaplan and A. E. Nelson, Phys. Lett. B **175**, 57 (1986)
[43] D. B. Kaplan and A. E. Nelson, Phys. Lett. B **179**, 409, Erratum (1986)
[44] G. E. Brown, C.-H. Lee, M. Rho and V. Thorsson, Nucl. Phys. A **567**, 937 (1994)
[45] V. Thorsson, M. Prakash and J. M. Lattimer, Nucl. Phys. A **572**, 693 (1994)
[46] C.-H. Lee, Phys. Rep. **275**, 255 (1996)
[47] N. K. Glendenning and J. Schaffner-Bielich, Phys. Rev. Lett. **81**, 4564 (1998)