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Are Neutron Stars Rich In H-dibaryons?

Jesper Leong,[a,*] **Anthony W. Thomas**[a] **and Pierre A. M. Guichon**[a]

[a] *CSSM and ARC Centre of Exellence for Dark Matter Particle Physics, Department of Physics, University of Adelaide, South Australia 5005, Australia*

E-mail: jesper.leong@adelaide.edu.au

The possible existence of an H-dibaryon near the $\Lambda - \Lambda$ threshold has still not been decided experimentally. This raises the question of the potential effects on neutron stars if it does exist. We explore the consequences within the quark-meson coupling model, using the excluded volume formalism. While the H is abundant in heavy stars the maximum mass is only lowered slightly by its presence.

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*Speaker

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1. Introduction

The H-dibaryon is a 6-quark, spinless boson with isospin zero and baryon number 2 [1]. Its composition is uuddss. Theoretical studies of the H have concluded that the H, if it exists, is likely to have a mass around the $\Lambda - \Lambda$ threshold [2–5]. The elusive H has so far evaded experimental detection with the current lower limit at $M_H > 2224$ MeV [6]. However, there is a possibility that the H could exist within the cores of neutron stars (NS). Here we examine this issue within the framework of the quark-meson coupling (QMC) model, starting with its effects on the equation of state (EoS) of dense matter in β-equilibrium.

Heavy NS have a mass of order 2 $M_\odot$ or more, giving them an inner core density of around $0.8 - 1.0$ fm^{-3} [7–11]. At these densities the argument for hyperons in β-equilibrium is particularly strong. The Λ is the first hyperon to appear, at just above 3 n_0 in QMC [12–14]. Since the mass of the H is thought to be near the $\Lambda - \Lambda$ threshold, then the H, should it exist, would be expected to occur shortly after the Λ. However, like the hyperons, the H should lower the predicted maximum mass of the NS. This effect is expected to be more severe in the case of the H, since it is a boson with zero momentum, but this is countered by the interaction of the H with the surrounding baryonic medium [15, 16].

There has only been a handful of work modeling the appearance of the H in NS [15–18]. The intermediate range forces involving the H are created by the scalar and vector mesons with the coupling strengths $g_{\sigma,H}$ and $g_{\rho,H}$. These are often fitted under the assumption that the H is present within the star, matching available NS observations [15, 18]. QMC is attractive in terms of modeling the H because the coupling strengths are predicted within the theory and there is no freedom to adjust $g_{\sigma,H}$ and $g_{\rho,H}$. Either the H exists and is capable of producing a heavy mass star, or it is incompatible.

In the following section we outline the formalism of incorporating the H into the nuclear EoS. The theory used here is QMC with the excluded volume effect (EVE), with its details available in Refs. [14, 19, 20]. The results are then presented with heavy NS constraints and the ramifications of these are discussed. We finish with a short conclusion on whether NS are really H-matter stars.

2. QMC Equation of State with the H-particle

The Lagragian for the H uses a minimal coupling scheme suggested by [15].

$$\mathcal{L}_D = \mathcal{D}^*_\mu H^* \mathcal{D}^\mu H - {M^*_H}^2 H^* H \,. \tag{1}$$

Here $\mathcal{D}_\mu$ is defined as $\mathcal{D}_\mu = \partial_\mu + i g_{\omega,H}\omega_\mu$, which is the standard replacement for the vector ω field. M^*_H is the effective mass and in QMC is given in equation (5). The equation of motion for the H is presented in Ref. [15]. Of immediate concern is the energy density and the mean-field contributions. Since the H does not carry isospin, only the σ and ω field equations are changed. The modifications to the mean fields are given in Eqs. (2) and (3) as follows:

$$m_\sigma{}^2\sigma + \lambda_3 \frac{g_\sigma{}^3}{2}\sigma^2 = \sum_f n^s_f - \frac{\partial M^*_H}{\partial \sigma} n_H, \tag{2}$$

$$m_\omega{}^2\omega = \sum_f g_{\omega,f} n^v_f + g_{\omega,H} n_H \,. \tag{3}$$

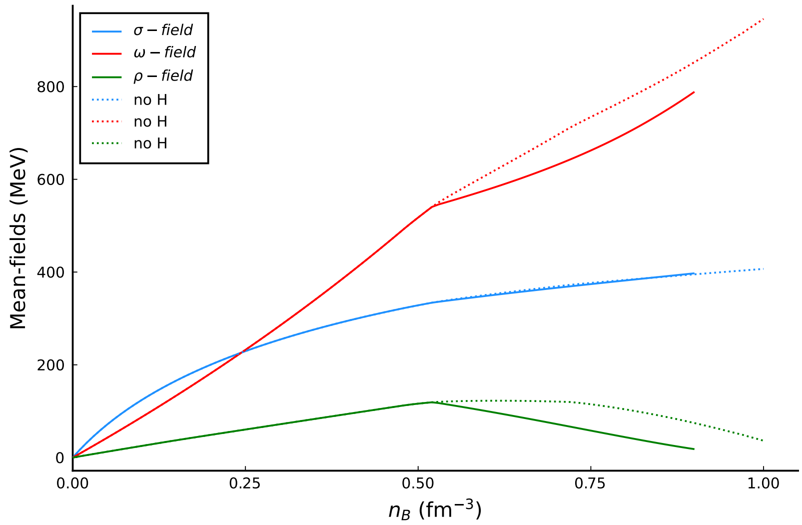

Figure 1: The mean-fields with neutron couplings are shown, with and without the H dibaryon. $M_H = 2247$ MeV is used here.

The λ_3 coefficients adjust the strength of the self interaction term necessary to lower the incompressibility [21]. $g_{\omega,H} = \frac{4}{3}g_{\omega,N}$, the strength of the coupling of the H to the ω field, is set by simple counting of non-strange quarks. This is the same scheme used in Ref. [15]. n_f^s and n_f^v are the scalar and vector densities, with the summation over n, p, Λ, Ξ^0, and Ξ^-. The Σ and Δ have previously been shown not to appear as discussed in Refs. [20, 22]. The contribution to the energy density is

$$\epsilon_H = 2{M_H^*}^2 H^* H = M_H^* n_H \,. \tag{4}$$

We see that the H does not contribute directly to the pressure but there is an indirect contribution through the modification of the mean-fields described in Eqs. (2) and (3). These resulting changes to the mean-fields are displayed in Fig. 1.

$$\begin{aligned} M_H^* &= M_H - 2\times[0.6672 + 0.04638 R_H - 0.0022 {R_H}^2] g_\sigma \sigma \\ &+2\times[0.00146 + 0.0691 R_H - 0.00862 {R_H}^2](g_\sigma \sigma)^2 \,. \end{aligned} \tag{5}$$

The effective masses for the baryon octet in QMC are given in Ref. [23]. To model M_H^*, we note that the H has twice the quark composition of the Λ. In QMC the mesons only couple to the u and d quarks. Note that the scalar polarisability, d, encodes the strength of the 3-body force on the H. This is known to be sensitive to the free bag radius in the MIT bag model, R_N^{free}, which is used to confine the quarks. Because the H is a 6-quark state, R_H^{free} is bigger than R_N^{free}. Mulders and Thomas found that $R_H^{free} = 1.2 \times R_N^{free}$ [2]. Thus the effective mass of the H is expressed as above in Eq. (5). We use $M_H = [2247, 2258, 2269]$ MeV as suggested in Ref. [5].

NS are taken to be at zero temperature and electrically neutral. The β-equilibrium condition must satisfy electrical charge and baryon number conservation. The H is electrically neutral but has a baryon number of 2. Thus, the total baryon number density is $n_B = \sum_f n_f + 2n_H$, where n_f is summed over the baryons and n_H is the density of the H.

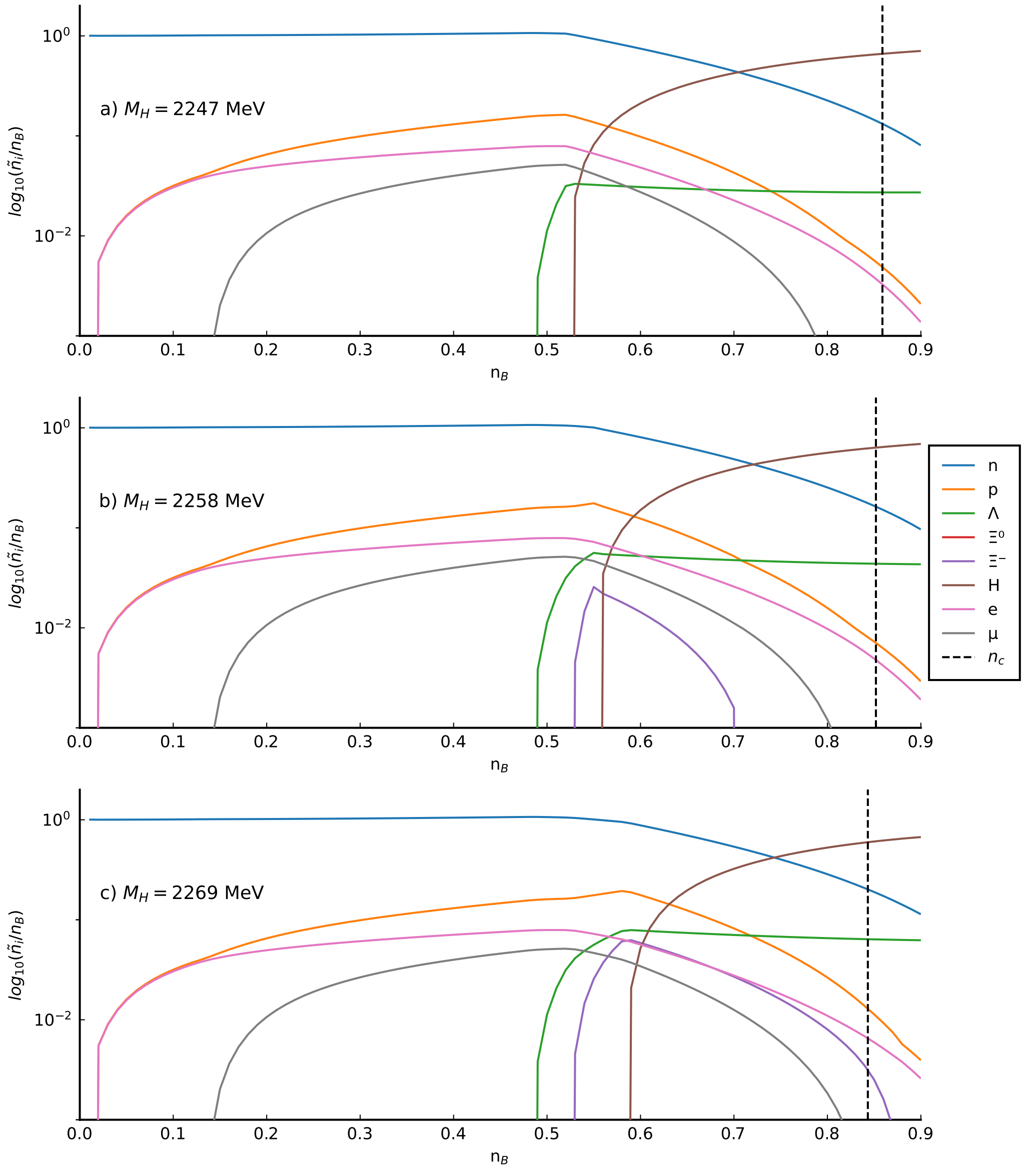

Figure 2: The EVE species fractions for a) $M_H = 2247$ MeV, b) $M_H = 2258$ MeV, and c) $M_H = 2269$ MeV. The black dashed lines indicate the central number density, n_c, of the maximum mass NS.

To model the short distance repulsion crucial to the NS EoS [13, 24] acting on all baryons, and the H, we use the excluded volume correction [25] previously used to analyse the case with only nucleons and hyperons [14]. The EVE number density is $\tilde{n}_f = \frac{n_f}{(1-v_0 n_B)}$, with n_B defined above. Thus, we interpreted this as H having twice the excluded volume, v_0, as the other baryons. For ease of comparison, we have chosen to use the same QMC parameters and a hard-core radius of $r = 0.45$ fm as used in Ref. [14], unless otherwise indicated.

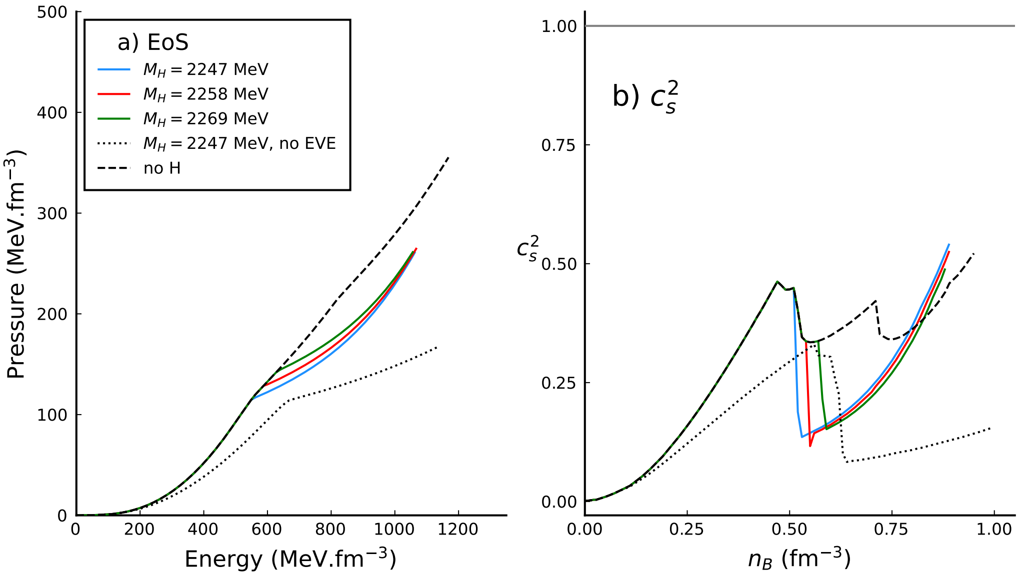

Figure 3: In a) we display the EoS with the accompanying b) speed of sound relative to light squared, c_s^2. We have included the EoS without the H from Ref. [14] as the black dashed line. The dotted black curve are the results for $M_H = 2247$ MeV without the EVE.

3. Results and Discussion

Fig. 2 displays how the H particle affects the NS composition. We first note that since the chosen $M_H > 2M_\Lambda$, the H never appears before the Λ hyperon. The larger M_H, the larger the density when it appears. The appearance of the H increases the threshold density of the Ξ^0, and as a consequence, no longer appears within the NS. For $M_H = 2247$ MeV, Ξ^- is also not present. Whether $\Xi^{0,-}$ appears is dependent on how soon the H-dibaryon appears. The vertical black lines indicate the central density (n_c) of the maximum mass neutron star. For larger M_H values, the central density is actually smaller. The H does alter the abundances of the nucleons and the hyperons, and near maximum, the H is the most populous particle within the cores of heavy NS.

In Fig. 3 we show the results for a) the EoS and b) c_s^2, which is the speed of sound squared. EoS with H have less pressure than without H. We have added an additional EoS for $M_H = 2247$ MeV, without the excluded volume correction, to show that the QMC coupling strengths for $g_{\sigma,H}$ and $g_{\omega,H}$ can appropriately describe a star which is stable against compression. The massive loss of pressure corresponding to the appearance of the H, and $c_s^2 > 0$, indicates that the values of $g_{\sigma,H}$ and $g_{\omega,H}$ used in the QMC model do not lead to an unstable star.

It is known that the EVE may violate causality at higher densities. In Fig. 3 b) we show that $c_s^2 < 1$ in all cases, which satisfies relativity. It is interesting to see that with the H, the EoS is actually stiffer at high density. When the H appears at around $0.5 - 0.6$ fm^{-3} there is a significant loss of neutron degeneracy pressure. The same is true for hyperons. Without the H, the Ξ^0 appears at a little over 0.7 fm^{-3} [14], as seen by the dashed line falling suddenly in Fig. 3 b). Recall that the appearance of the H actually increases the threshold for the Ξ^0 above n_c for a maximum mass NS. Thus, when the H is present, there is no further softening of the EoS by the Ξ^0 (and Ξ^- for

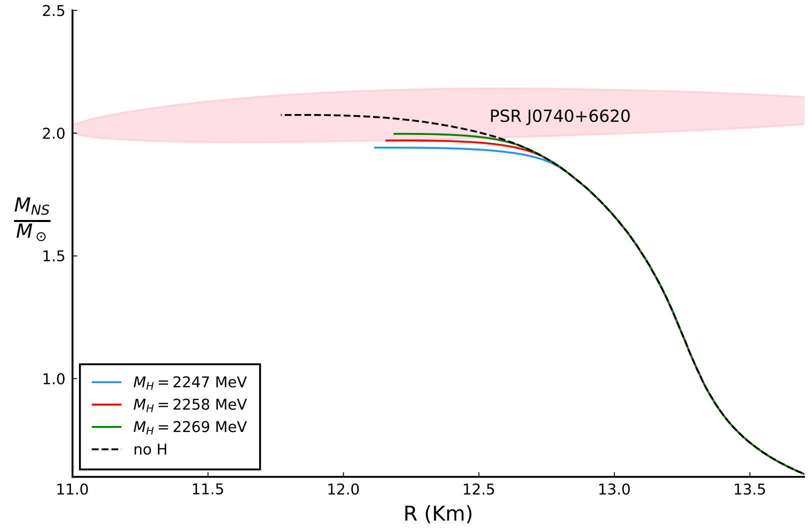

Figure 4: The TOV equation is used to produce the mass-radius curve for each of the EoS. The observed NS constrained used here is PSR J0740+6620 [27].

M_H = 2247 MeV). However, without the H, the EoS does suffer from further softening from the appearance of the Ξ hyperons.

The stiffer EoS at high densities, when the H is included, does not, however, translate to heavier NS. In Fig. 4 we show that the introduction of the H leads to a slight reduction of M^{NS}_{Max}. The closer M_H lies to the $\Lambda - \Lambda$ threshold, the more the decrease in M^{NS}_{Max}. Once the H appears the softening of the EoS leads to a mass plateau where the mass of the star hardly rises but becomes more and more compact. The results also show that smaller M_H leads to a smaller radius at M^{NS}_{Max}. Note that the H does not appear for low mass stars and thus the tidal deformability is unaffected at $\Lambda_{1.4} = 560$ [26].

4. Conclusion

Our results do indicate that the H particle can be successfully incorporated into QMC with natural couplings to the σ and ω fields. With $g_{\sigma,H}$ and $g_{\omega,H}$ fixed, the mass of the H determines the density at which the H appears at β-equilibrium. The H appears shortly after the Λ hyperon and leads to only a slight reduction of the NS maximum mass. The H is highly abundant and in the heaviest of NS, it is predicted to be dominant, suggesting that the cores of these stars have a sizable H-matter condensate.

References

[1] R. L. Jaffe, *Perhaps a Stable Dihyperon*, Phys. Rev. Lett. 38 (1977) 195–198, [Erratum: Phys.Rev.Lett. 38, 617 (1977)]. doi:10.1103/PhysRevLett.38.195.

[2] P. J. Mulders, A. W. Thomas, *Pionic Corrections and Multi - Quark Bags*, J. Phys. G 9 (1983) 1159. doi:10.1088/0305-4616/9/10/005.

[3] T. Inoue, S. Aoki, T. Doi, T. Hatsuda, Y. Ikeda, N. Ishii, K. Murano, H. Nemura, K. Sasaki, *Two-baryon potentials and H-dibaryon from 3-flavor lattice QCD simulations*, Nuclear Physics A 881 (2012) 28–43, progress in Strangeness Nuclear Physics. doi:https://doi.org/10.1016/j.nuclphysa.2012.02.008.
URL https://www.sciencedirect.com/science/article/pii/S0375947412000760

[4] S. R. Beane, E. Chang, S. D. Cohen, W. Detmold, H. W. Lin, T. C. Luu, K. Orginos, A. Parreno, M. J. Savage, A. Walker-Loud, *Light Nuclei and Hypernuclei from Quantum Chromodynamics in the Limit of SU(3) Flavor Symmetry*, Phys. Rev. D 87 (3) (2013) 034506. arXiv:1206.5219, doi:10.1103/PhysRevD.87.034506.

[5] P. E. Shanahan, A. W. Thomas, R. D. Young, *Updated Analysis of the Mass of the H Dibaryon from Lattice QCD*, JPS Conf. Proc. 1 (2014) 013028. arXiv:1308.1748, doi:10.7566/JPSCP.1.013028.

[6] H. Takahashi, et al., *Observation of a (Lambda Lambda)He-6 double hypernucleus*, Phys. Rev. Lett. 87 (2001) 212502. doi:10.1103/PhysRevLett.87.212502.

[7] J. Antoniadis, et al., *A Massive Pulsar in a Compact Relativistic Binary*, Science 340 (2013) 6131. arXiv:1304.6875, doi:10.1126/science.1233232.

[8] T. E. Riley, et al., *A NICER View of the Massive Pulsar PSR J0740+6620 Informed by Radio Timing and XMM-Newton Spectroscopy*, Astrophys. J. Lett. 918 (2) (2021) L27. arXiv:2105.06980, doi:10.3847/2041-8213/ac0a81.

[9] E. Fonseca, et al., *Refined Mass and Geometric Measurements of the High-mass PSR J0740+6620*, Astrophys. J. Lett. 915 (1) (2021) L12. arXiv:2104.00880, doi:10.3847/2041-8213/ac03b8.

[10] Z. Arzoumanian, et al., *The NANOGrav 11-year Data Set: High-precision timing of 45 Millisecond Pulsars*, Astrophys. J. Suppl. 235 (2) (2018) 37. arXiv:1801.01837, doi:10.3847/1538-4365/aab5b0.

[11] R. W. Romani, D. Kandel, A. V. Filippenko, T. G. Brink, W. Zheng, *PSR J0952−0607: The Fastest and Heaviest Known Galactic Neutron Star*, Astrophys. J. Lett. 934 (2) (2022) L17. arXiv:2207.05124, doi:10.3847/2041-8213/ac8007.

[12] T. F. Motta, P. A. M. Guichon, A. W. Thomas, *On the sound speed in hyperonic stars*, Nucl. Phys. A 1009 (2021) 122157. arXiv:2009.10908, doi:10.1016/j.nuclphysa.2021.122157.

[13] J. Leong, T. F. Motta, A. W. Thomas, P. A. M. Guichon, *Dense nuclear matter with phenomenological short distance repulsion*, Phys. Rev. C 108 (1) (2023) 015804. doi:10.1103/PhysRevC.108.015804.

[14] J. Leong, A. W. Thomas, P. A. M. Guichon, *Excluded volume effects on cold neutron star phenomenology*, Nucl. Phys. A 1050 (2024) 122928. arXiv:2308.08987, doi:10.1016/j.nuclphysa.2024.122928.

[15] N. K. Glendenning, J. Schaffner-Bielich, *Neutron star constraints on the H dibaryon*, Phys. Rev. C 58 (1998) 1298–1305. arXiv:astro-ph/9803232, doi:10.1103/PhysRevC.58.1298.

[16] A. Faessler, A. J. Buchmann, M. I. Krivoruchenko, *Constraints to coupling constants of the omega- and sigma mesons with dibaryons*, Phys. Rev. C 56 (1997) 1576–1581. arXiv:nucl-th/9706080, doi:10.1103/PhysRevC.56.1576.

[17] R. Tamagaki, *Implications of the H dihyperon in high density hadronic matter*, Prog. Theor. Phys. 85 (1991) 321–334. doi:10.1143/PTP.85.321.

[18] X. Wu, L. Wang, H.-T. An, M. Ju, H. Shen, *Properties of H particle-admixed compact star* (2 2024). arXiv:2402.14288.

[19] P. A. M. Guichon, J. R. Stone, A. W. Thomas, *Quark–Meson-Coupling (QMC) model for finite nuclei, nuclear matter and beyond*, Prog. Part. Nucl. Phys. 100 (2018) 262–297. arXiv:1802.08368, doi:10.1016/j.ppnp.2018.01.008.

[20] J. Rikovska-Stone, P. A. M. Guichon, H. H. Matevosyan, A. W. Thomas, *Cold uniform matter and neutron stars in the quark-mesons-coupling model*, Nucl. Phys. A 792 (2007) 341–369. arXiv:nucl-th/0611030, doi:10.1016/j.nuclphysa.2007.05.011.

[21] K. M. L. Martinez, A. W. Thomas, J. R. Stone, P. A. M. Guichon, *Parameter optimization for the latest quark-meson coupling energy-density functional*, Phys. Rev. C 100 (2) (2019) 024333. arXiv:1811.06628, doi:10.1103/PhysRevC.100.024333.

[22] D. L. Whittenbury, J. D. Carroll, A. W. Thomas, K. Tsushima, J. R. Stone, *Quark-Meson Coupling Model, Nuclear Matter Constraints and Neutron Star Properties*, Phys. Rev. C 89 (2014) 065801. arXiv:1307.4166, doi:10.1103/PhysRevC.89.065801.

[23] P. A. M. Guichon, A. W. Thomas, K. Tsushima, Binding of hypernuclei in the latest quark-meson coupling model, Nucl. Phys. A 814 (2008) 66–73. arXiv:0712.1925, doi:10.1016/j.nuclphysa.2008.10.001.

[24] R. M. Aguirre, A. L. De Paoli, *Neutron star structure in a quark model with excluded volume correction*, Phys. Rev. C 68 (2003) 055804. arXiv:nucl-th/0211038, doi:10.1103/PhysRevC.68.055804.

[25] D. H. Rischke, M. I. Gorenstein, H. Stoecker, W. Greiner, *Excluded volume effect for the nuclear matter equation of state*, Z. Phys. C 51 (1991) 485–490. doi:10.1007/BF01548574.

[26] B. P. Abbott, et al., *GW170817: Measurements of neutron star radii and equation of state*, Phys. Rev. Lett. 121 (16) (2018) 161101. arXiv:1805.11581, doi:10.1103/PhysRevLett.121.161101.

[27] T. Salmi, et al., The Radius of the High-mass Pulsar PSR J0740+6620 with 3.6 yr of NICER Data, Astrophys. J. 974 (2) (2024) 294. arXiv:2406.14466, doi:10.3847/1538-4357/ad5f1f.