《原子核物理评论》

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在线阅读 View online: https://doi.org/10.11804/NuclPhysRev.41.QCS2023.09

引用格式:

李昂. 中子星研究是否存在“超子危机”？[J]. 原子核物理评论, 2024, 41(3):834-838. doi: 10.11804/NuclPhysRev.41.QCS2023.09

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第 41 卷 第 3 期
2024 年 9 月

原 子 核 物 理 评 论
Nuclear Physics Review

Vol. 41，No. 3
Sep.，2024

Article ID: 1007-4627(2024)03–0834–05

Is There a “hyperon puzzle” Problem in Neutron Star Study?

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Abstract: Neutron star physics has wrestled with the longstanding challenge of the hyperon puzzle, attempting to reconcile lowered theoretical predictions of maximum masses due to hyperons with astrophysical observations based on the measured masses of the heaviest pulsars. In this study, we conduct a comprehensive statistical analysis of equations of state (EoS) for neutron stars with hyperons, including both laboratory data and astrophysical observations. Results from the statistical analysis reveal the important role of the correlations between the scalar and vector channels of hyperon-nucleon interactions deduced from available Λ-separation-energy data of single Λ hypernuclei. The analysis preliminarily quantifies uncertainties in hyperon star properties due to the uncertain hyperon-nucleon interaction in dense matter, and the maximum mass of hyperon star is found to reach $\sim 2.2\,M_{\odot}$, challenging the existence of the hyperon puzzle. As part of a broader initiative connecting nuclear physics and astronomy to quantitatively determine neutron star EoS, the study provides valuable insights into the hyperon puzzle and its implications for our understanding of neutron star interiors. Moreover, the investigation addresses the lack of precise knowledge regarding hyperonic interactions, emphasizing the need for additional hypernuclear data through a combined effort involving theory, experiments, and observations.

Key words: neutron star; equation of state; hyperon; hypernuclei

CLC number: O571.53　　**Document code:** A

DOI: 10.11804/NuclPhysRev.41.QCS2023.09　　**CSTR:** 32260.14.NuclPhysRev.41.QCS2023.09

0 Introduction

“What is the nature of neutron stars and dense nuclear matter?” is one of the important questions in the field of nuclear astrophysics[1−2]. Establishing a theoretical model capable of accurately explaining nuclear matter data across diverse scenarios, spanning both laboratory experiments and astronomical observations of neutron stars, is an arduous undertaking. In this paper of QCS2023 Special Issue, we tackle a specific challenge in the quest to determine nuclear force and neutron star properties through multimessenger astronomy: “Is there a hyperon puzzle problem in neutron star study?”.

In neutron stars, nuclear matter exists in beta equilibrium, ranging from very low density to several times the saturation density ($\rho \approx 0.16\ \mathrm{fm}^{-3}$) and is extremely neutron-rich[3−6]. Numerous model calculations in the literature suggest a central density as high as $(2\sim10)\rho_0$ for the maximum mass, with the possibility of strangeness-driven phase transitions occurring in the innermost regions of neutron stars[1]. Hyperons (Y), such as Λ hyperons from the lightest baryon octet $J^P=(1/2)^+$, may appear in high-density neutron-star cores via weak interaction process $p+e^- \longrightarrow \Lambda+\nu_e$, replacing highly energetic neutrons when the Λ chemical potential fulfills the condition $\mu_\Lambda=\mu_n=\mu_p+\mu_e$. Other higher-mass hyperon species (Σ and Ξ hyperons) may also appear. While hyperons are unstable under terrestrial conditions, they remain stable in dense stellar matter, forming an inner hyperon core and an outer nucleon shell in the core of a massive neutron star.

Efforts to decipher the composition of neutron stars, including hyperons, have been ongoing since the suggestion of their possible presence by Gameron[7]. However, the parameters of the hyperonic interaction remain insufficiently constrained, and there are still many theoretical and experimental ambiguities regarding baryon interactions in the strangeness sector. One interesting possibility is that the formation of hyperons inside neutron stars might lead to a significant softening of the equation of state (EoS) of a neutron-star core, with respect to the $npe\mu$ case, and lower the theoretical maximum mass below the observed pulsar masses, causing the well-known hyperon puzzle problem[8−9].

Despite accumulated laboratory data on hypernuclei, surpassing 40 Λ-hypernuclei, a few $\Lambda\Lambda$-hypernuclei, and Ξ-hypernuclei, challenges persist in understanding the hy-

Received date: 31 Dec. 2023;　**Revised date:** 25 Jun. 2024

Foundation item: National SKA Program of China (2020SKA0120300); National Natural Science Foundation of China (12273028)

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pernuclear force. Previous studies[9] have utilized both single and double hypernuclei data to investigate the effects of hyperon interactions on the global properties of neutron star matter. In particular, it was found that, to be consistent with the result given by "NAGARA event", the YY interaction should be weakly attractive and the maximum mass of neutron stars including hyperons was found to be around $1.75\,M_\odot$ when taking TM1 parameter set[10] as nucleon parametrization①. Still, moving beyond these model calculations requires exploring the potential integration of neutron star multimessenger observations with hypernuclei experiments to gain deeper insights into the hypernuclear force: Is it possible to combine neutron star multi-messenger observations with hypernuclei experiments to understand better the hypernuclear force? How to combine them? What new information can we learn?

The paper is organized as follows: Section 1 briefly introduces the employed model and the Bayesian analysis method, including the used neutron star observations and the $R_{\sigma\Lambda}$ - $R_{\omega\Lambda}$ relation from hypernuclei data. We present our results and a discussion in Section 2 and summarize our paper in Section 3.

1 Model and analysis method

The hyperonic interaction parameters in terms of an exchange of mesons, are hyperon-meson coupling constants. We denote these constants as $R_{mY} = g_{mY}/g_{mN}$ ($m = \sigma,\omega,\rho,\delta$)②. Assuming SU(6) symmetry for the ω - Λ -hyperon coupling ($R_{\omega\Lambda} = 2/3$), the σ - Λ -hyperon coupling can be derived by extrapolating the experimental binding energy of single- Λ hypernuclei to $A^{-2/3} = 0$: $R_{\sigma\Lambda} \approx 0.61$, corresponding to $U_\Lambda(\rho_0) = -30$ MeV [12]. Nevertheless, it is still uncertain to determine the fit to hypernuclear data. The broken SU(3) flavor symmetry seems inevitable to account for the different attractive/repulsive nature of hyperon potentials[13] and to meet mass measurements of heavy pulsars[14]. In our analysis, we relax the symmetry argument, treating $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ as free parameters between 0 and 1. By doing so, we have reasonably considered a positive and smaller hyperon coupling compared to nucleons[15].

Recently, a linear correlation between $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ was found by fitting calculated Λ separation energies to experimental values of eleven known Λ hypernuclei with $A \geqslant 12$ [16]: *i.e.*, $R_{\omega\Lambda} = 1.228R_{\sigma\Lambda} - 0.097$. We incorporate this empirical relation (NUCL.) into our study, utilizing the statistical error of $R_{\sigma\Lambda}$ in Rong *et al.*[16]. For details on the empirical relation and choices of statistical error, refer to Sun *et al.*[17].

In our study, we confront the phenomenological hyperonic interaction to the recently observed neutron star properties (like mass M, radius R and tidal deformability Λ), performing Bayesian inference for the hyperon-meson couplings from the robust LIGO/Virgo tidal measurement of the GW170817 binary neutron star merger[18] as well as two NICER mass-radius measurements of pulsars (PSR J0030+0451[19−20] and PSR J0740+6620[21−22]). For a comprehensive understanding of how we incorporate mass, radius, and tidal deformability data, see Ref. [17]. With priors and likelihood established, we sample from the posterior distribution using the python-based bilby and pymultinest packages. Our aim is to explore constraints on Λ hyperon coupling constants based on current neutron star measurements and discuss parameter spaces for hyperon star properties. As highlighted by Huang *et al.*[23], this methodology offers the advantage of potentially discussing matter composition or nuclear properties once the inference is completed.

Given the limited experimental information on Σ and Ξ hypernuclei, we set the vector- Σ,Ξ hyperon couplings based on SU(6) symmetry. Scalar-coupling values for Σ,Ξ hyperons ($R_{\sigma\Sigma} = 0.443$, $R_{\sigma\Xi} = 0.302$)[24] reproduce reasonable single-particle mean-field potentials in symmetric nuclear matter at the saturation density ρ_0: $U_\Sigma(\rho_0) = +34$ MeV [13] and $U_\Xi(\rho_0) = -14$ MeV [25−26]. For the isospin-vector scalar channel, we adopt $R_{\delta\Sigma} = R_{\sigma\Sigma}$ and $R_{\delta\Xi} = R_{\sigma\Xi}$ [27−28].

2 Results and discussion

We conduct a statistical analysis involving 17 stiff EoSs, namely NL3 $\omega\rho$ [29], LHS[30], RMF201[31], NL3[32], Hybrid[33], TM2[10], NLSV1[34], PK1[35], S271v6[36], HC[37], DD-LZ1[38], DD-ME2[39], DD2[40], PKDD[35], OMEG[41], DD-PC1[42], FKVW[43], PC-PK1[44]. These EoSs are chosen based on their capability to support a pure neutron star with a mass of $\geqslant 2.3\,M_\odot$ with varying stiffness. This selection ensures flexibility for potential EoS softening with the inclusion of hyperons, aiming to explain the masses observed in the heaviest pulsars, approximately $\sim 2\,M_\odot$, found in binaries with white dwarfs[45−48]. The considered relativistic mean-field (RMF) effective interactions encompass both finite-range and zero-range (contact interactions). The employed linear $R_{\sigma\Lambda}$ - $R_{\omega\Lambda}$ relations are demonstrated to be consistent with both finite-range and zero-range models (see Appendix in Sun *et al.*[17]). These interactions can reproduce the nuclear properties such as nuclear saturation and nuclear symmetry energy given by

①We mention here that extending the scalar field, for example, with a σ -cut potential, could increase this maximum mass value. For detailed discussions, see Zhang *et al.*[11].

②Strange mesons can be further incorporated[9], for example, to account for YY interaction when considerable double hypernuclei data become available.

finite-nuclei and heavy-ion experiments. Additionally, the effective interactions account for medium dependence, incorporating higher-order many-body effects by either including non-linear meson self-interaction terms or assuming an explicit density dependence for the meson-nucleon couplings.

We specifically focus on the NL3 $\omega\rho$ EoS, one of the stiffest ones in the literature, to explore quantitative aspects of hyperon stars in light of statistical results obtained with NL3 $\omega\rho$. This analysis offers insights into the uncertainties associated with hypernuclear matter and hyperon star properties, given the uncertain hyperon-nucleon interaction in dense matter. Table 1 presents the most probable values and 68% credible boundaries of the scalar and vector coupling ratios ($R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$), constrained by both astrophysical and laboratory data. Fig. 1 visually compares the results of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ from astrophysical and laboratory data. Additionally, Table 2 compiles various hyperon star properties derived under the most probable hyperonic interaction from the joint +NICER+GW170817+NUCL analysis. Figs. 2 and 3 depict the mass versus radius & density relations and the composition of hyperon stars, respectively, in comparison with corresponding neutron star results.

Table 1　Most probable intervals of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ (68% credible intervals) for a representative effective interaction (NL3 $\omega\rho$) constrained by multimessenger neutron star data with or without constraints from laboratory data.

	Prior	+NICER +GW170817	+NICER +GW170817 +NUCL
$R_{\sigma\Lambda}$	$U(0,1)$	$0.420^{+0.448}_{-0.294}$	$0.712^{+0.157}_{-0.215}$
$R_{\omega\Lambda}$	$U(0,1)$	$0.777^{+0.127}_{-0.269}$	$0.778^{+0.121}_{-0.183}$

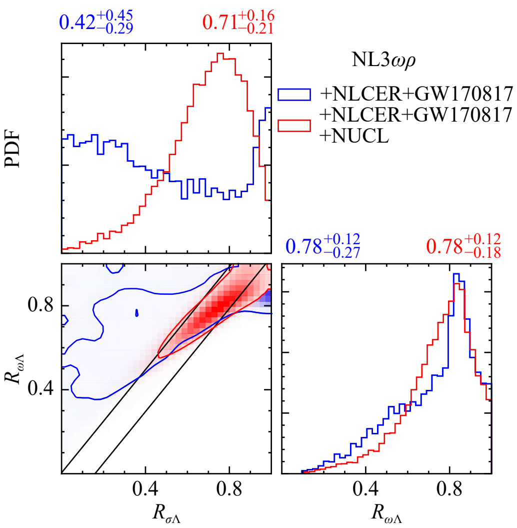

Fig. 1　(color online) Comparison of the posterior distributions of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ with (in red) and without (in blue) the empirical hypernuclei constraint. The laboratory $R_{\sigma\Lambda}$ - $R_{\omega\Lambda}$ relation, deduced from the measured Λ separation energy in single Λ hypernuclei, is also indicated with two black lines. The contours are the 68% credible regions for the parameters using the NL3 $\omega\rho$ EoS. Taken from Sun *et al.*[17].

Table 2　Most probable intervals of various hyperon star properties for a representative effective interaction (NL3 $\omega\rho$), to the 68% confidence level, constrained jointly by the +NICER+GW170817+NUCL analysis. The corresponding results of neutron stars (without hyperons) are also shown. $M_{\max}$ is the maximum mass and ρ_c/ρ_0 is the corresponding central density scaled by the saturation density. $R_{2.0}$ is the radius of $2.0\,M_\odot$ stars. $R_{1.4}$ and $\Lambda_{1.4}$ are the radius and tidal deformability of $1.4\,M_\odot$ stars, respectively. Taken from Sun *et al.*[17].

	$M_{\max}/M_\odot$	ρ_c/ρ_0	$R_{2.0}$/km	$R_{1.4}$/km	$\Lambda_{1.4}$
w.o. Y	2.756	4.676	14.070	13.772	941.852
with Y	$2.176^{+0.085}_{-0.202}$	$4.846^{+0.046}_{-0.501}$	$13.968^{+0.096}_{-1.512}$	$13.769^{+0.000}_{-1.084}$	$940.165^{+0.000}_{-443.756}$

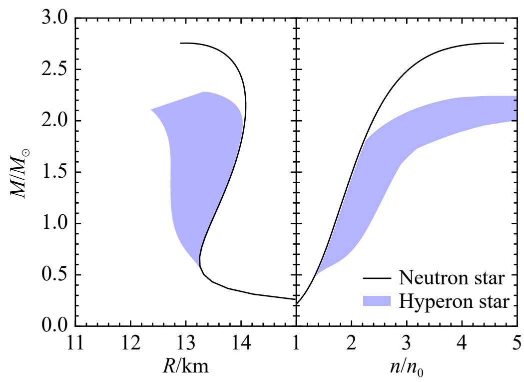

Fig. 2　(color online) The most probable mass versus radius & density relations of hyperon stars from the joint analysis (at 68% credible level) of the multimessenger neutron star observations from LIGO/Virgo and NICER, in combination with the study of hypernuclei, compared to those of neutrons stars. Taken from Sun *et al.*[17].

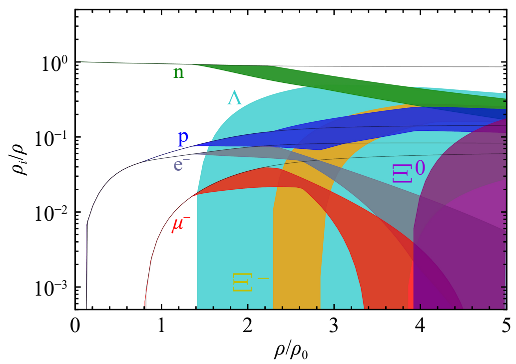

Fig. 3　(color online) Particle fractions of beta-stable hypernuclear matter as a function of the baryon density (scaled by the nuclear saturation density ρ_0), with the most probable hyperonic interaction from the joint +NICER+GW170817+NUCL analysis (at 68% credible level) for the representative NL3 $\omega\rho$ model. Taken from Sun *et al.*[17].

An observation from Table 1 is that the hypernuclei constraint tends to favor larger values of $R_{\sigma\Lambda}$ and $R_{\omega\Lambda}$ while disfavoring smaller values for both couplings. The strong underlying $R_{\sigma\Lambda}$ - $R_{\omega\Lambda}$ correlation imposed by the data of single Λ hypernuclei ensures a large enough scalar hyperon coupling to match the large vector hyperon coupling. The incorporation of astrophysical observational data only slightly adjusts this correlation (indicated with two black lines in Fig. 1) towards smaller values of $R_{\omega\Lambda}$.

Despite the dependence on uncertain hyperonic interaction, generic features emerge, indicating that the introduction of hyperons softens the EoS. This softening occurs as the Fermi pressure of neutrons and protons is relieved near the top of their Fermi seas by allowing them to hyperonize to unoccupied low-momentum states, resulting in lower pressure. Consequently, neutron stars containing hyperons are more compact, with the maximum mass reduced by approximately 20% (*e.g.*, from 2.7 to $\sim 2.2\,M_\odot$ in the NL3 $\omega\rho$ case). The stellar radius is smaller above $\sim 0.5\,M_\odot$ and increases with stellar mass. One important thing to notice is that, according to the NL3 $\omega\rho$ EoS, at the 68% credible level, the maximum mass of a hyperon star is $M_{\max} = 2.176^{+0.085}_{-0.202}\,M_\odot$, with the peak value around $\sim 2.26\,M_\odot$ given the current determination of hyperonic interaction. This result is attributed to the strong correlation between the scalar and vector channels of YN interactions, ensuring sufficient vector repulsion and a prediction of hyperon stars with a sufficiently high maximum mass without encountering the hyperon puzzle problem. Quantitative differences among the adopted 17 models can be found in Sun *et al.*[17].

Nevertheless, as seen in Fig. 3 illustrating the particle composition, the imprecise knowledge of hyperonic interaction significantly influences the predicted hyperonic composition within the cores of neutron stars. Currently, it remains uncertain whether the lightest Λ of the baryon octet or the heavier, negatively-charged Ξ^- appears first. Additionally, the threshold density for Λ hyperons spans a wide range of ~(1.4~3.8) ρ_0. In the chosen strength of hyperonic interaction, three hyperon species (Λ, Ξ^-, Ξ^0) are present, while Σ hyperons are absent due to their repulsive interaction in the dense medium. Eventually, a more comprehensive dataset of hypernuclear information is essential for gaining a deeper understanding of hyperon interaction. This necessitates a combined effort involving theory, experiments, and observations to further unravel the complexities associated with hyperonic composition in neutron-star cores.

3 Summary and outlook

In this study, we tackle a longstanding challenge in neutron star physics, specifically the hyperon puzzle. By incorporating insight from hypernuclei calculations and adopting a more general treatment of hyperon couplings than currently present in the literature, we find indications that the hyperon puzzle may not exist. We believe that the methodology employed and the results obtained could hold significant implications for future research. This work represents a recent endeavor to quantitatively determine neutron star EoS by establishing a consistent connection between nuclear physics and astronomy. Previously, we provided a consistent description of a nucleon and many-body nucleonic system derived from a quark potential, taking into account heavy pulsar measurements, GW170817, and NICER observations of neutron stars③. Future extensions of this study could involve incorporating an effective Lagrangian with meson fields that mediate strong interactions between quarks in a quark mean-field model[52]. Additionally, there is potential for expansion to include the low-lying excitation spectrum of Λ hypernuclei[53].

It is important to note that, in this exploration, we simplify the procedure by focusing only on the preferred coupling constants of Λ hyperons, while maintaining fixed values for the Σ and Ξ hyperon couplings. Comprehensive studies on Σ and Ξ hyperon couplings should await substantial progress in understanding Σ, Ξ hypernuclei, as well as double hypernuclei, in the future.

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③For further extensions to neutron stars with a quark core and self-bound quark stars, see Miao *et al.*[49], Li *et al.*[50]. It is also interesting to consider multiple forms of exotic phases, including also Δ-resonances[51], to study their competition and coexistence.

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中子星研究是否存在“超子危机”?

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摘要: 中子星物理学长期以来一直致力于解决“超子危机”的难题，旨在协调因超子而降低的最大质量理论预测与基于最重脉冲星测量质量的天体物理观测。在最近的研究中，结合超核实验室数据和最新的中子星天文观测数据，初步量化分析了超子-核子相互作用引起的超子星性质的不确定性。研究发现，超子星的最大质量可达 $\sim 2.2\,M_{\odot}$。这一结果对"超子危机"难题的存在提出了挑战。这项工作是我们基于自洽连接核物理和天文学以定量确定中子星状态方程研究计划中的一个重要步骤，揭示了从单 Λ 超核数据中得出的超子-核子标量部分和矢量部分相互作用之间相关性的重要性。在未来的研究中，将进一步结合相关的理论、实验和观测，以更深入地探讨中子星状态方程的众多难题。

关键词: 中子星；状态方程；超子；超核

收稿日期: 2023-12-31； **修改日期:** 2024-06-25

基金项目: 科技部 SKA 专项 (2020SKA0120300)；国家自然科学基金资助项目 (12273028)

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