Hypernuclear Physics for Neutron Stars

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Abstract

The role of hypernuclear physics for the physics of neutron stars is delineated. Hypernuclear potentials in dense matter control the hyperon composition of dense neutron star matter. The three-body interactions of nucleons and hyperons determine the stiffness of the neutron star equation of state and thereby the maximum neutron star mass. Two-body hyperon-nucleon and hyperon-hyperon interactions give rise to hyperon pairing which exponentially suppresses cooling of neutron stars via the direct hyperon URCA processes. Non-mesonic weak reactions with hyperons in dense neutron star matter govern the gravitational wave emissions due to the r-mode instability of rotating neutron stars.

Key words: Hypernuclei, Nonmesonic Weak Decay, Strange Hadronic Matter, Neutron Stars, Maximum Mass, Cooling of Neutron Stars, R-Mode Instability, Gravitational Waves
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1 Introduction

Neutron stars are born in spectacular core collapse supernova explosions. These compact, massive objects have typical radii of about 10 km and masses of $(1-2)M_\odot$. Matter in the core of neutron stars is compressed to extreme densities, several times normal nuclear matter density, i.e. $\rho \gg \rho_0 = 3\cdot 10^{14}$ g/cm^3. The relation of supernova explosions being the birthplace of neutron stars is exemplified by the historic supernova remnant of AD 1054, the crab nebula, and the crab pulsar, a rotation-powered neutron star, sitting in its center.

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More than 1700 pulsars are recorded in the publicly available pulsar data base at the Australian National Telescope Facility [1]. The number of discovered pulsars is continuously growing with the ongoing pulsar surveys at radio telescopes worldwide (Arecibo, Green Bank Telescope, Parkes Multibeam). The best determined mass is still the one of the Hulse-Taylor pulsar with $M = (1.4411 \pm 0.00035)M_\odot$ [2], the fastest rotating one is the pulsar PSR J1748-2446ad with 716 revolutions per second [3].

Recently, indications of an extremely massive neutron star have been published [4,5]. If the measured periastron advance is due to effects from general relativity only, the pulsar PSR J1748-2021B has a mass of $M \geq (2.74 \pm 0.21)M_\odot$ and is more massive than $M \geq 2.0M_\odot$ with a confidence level of 99%. Note, that it can not be excluded at present that the system measured actually contains two neutron stars, not a single one. Redshifted spectral lines have been claimed to be extracted from the analysis of x-ray bursts from EXO 0748–676 [6], which give a constraint on the mass-radius ratio of the compact star. A recent analysis comes to the conclusion that the compact star mass is $M \geq (2.10 \pm 0.28)M_\odot$ with a radius of $R \geq (13.8 \pm 1.8)$ km [7] claiming that 'unconfined quarks do not exist at the center of neutron stars'! However, this conclusion was put into perspective in a follow-up reply [8] which demonstrated that those limits rule out soft equations of state, but not quark stars or hybrid stars. The interactions between quarks can be quite strong so that the presence of quark matter in the core stabilises the compact star. On the other hand, the mass limit provides indeed a strong constraint for hyperons in dense neutron star matter. Hyperons are likely to appear at moderate densities, which will substantially decrease the maximum mass. This conclusions is guided by hypernuclear data and present model calculations. If such massive neutron stars are confirmed in the future, say with masses above $2M_\odot$, then it seems that our present understanding of hypernuclear physics of compact stars will be in conflict with the pulsar data, as we will outline in more detail below.

Constraints on the mass and radius of neutron stars can be derived by observations in the optical as well as in the x-ray band, a booming field of exploration since the launch of the x-ray satellites Chandra and XMM-Newton in 1999. The best studied isolated neutron star is RXJ 1856.35-3754, the closest one known. A two-component blackbody fit to the combined optical and x-ray spectra results in a low soft temperature, so as not to be in contradiction with the observed x-ray flux. This low temperature implies a rather large radiation radius, the radius observed at infinity, $R_\infty = R/\sqrt{1 - 2GM/R}$, so that the optical flux comes out right. A conservative lower limit was given in [9] and confirmed in a detailed modelling of the neutron star atmosphere [10,11] as being $R_\infty \approx 17$ km for an assumed distance of $d = 140$ pc. With the derived gravitational redshift of $z_g \approx 0.22$, the true radius of the neutron star would be about $R \approx 14$ km with a corresponding mass of $M \approx 1.55M_\odot$. The large radiation radius implies generally a large neutron star radius which could only be explained with a stiff nuclear equation of state. The biggest uncertainty, besides the systematical one, is the distance to the neutron star.

The spectra of the neutron star X7 in the Globular Cluster 47 was fitted in Ref. [12] with an improved hydrogen atmosphere model. The radius of the neutron star was estimated to be $R_{\rm ns} = (14.5^{+1.8}_{-1.6})$ km, which is a little bit larger than for non-relativistic nuclear models but right in the range of standard relativistic mean-field models, see e.g. [13]. The authors of Ref. [12] state, that for a radius of 10 km the mass should be in the range $M_{\rm ns} = (2.20^{+0.03}_{-0.16}) M_\odot$. For a radius of 14 km, however, any mass between 0.5 and $2.3 M_\odot$ is allowed by the fit. On the other hand, atmosphere fits to the spectra of M13 lead to rather small radii, a radius of only $R = 9.77^{+0.09}_{-0.29}$ km was derived in Ref. [14]. The allowed ranges in the mass-radius diagram for the fit to the spectra of M13 and X7 are nearly mutually exclusive on the 99% confidence level. However, one should keep in mind, that the whole mass-radius curve for neutron stars just has to reach somewhere those two regions. In fact, many of the mass-radius curves shown in [14] pass the two constraints from the fits to the spectra of M13 and X7, except for the curves of the most stiffest models, in particular for the relativistic field theoretical models without hyperons.

Another way of probing neutron star matter properties is by cooling observations of supernova remnants, see e.g. [15,16]. The observational limits points towards fast cooling processes in the interior of neutron stars, i.e. direct URCA reactions. Standard conventional cooling curves are too high, so that either a large nuclear asymmetry energy or strange exotic particles are needed to generate efficient and fast cooling (see [17] for a theoretical review).

The basic structure of the low-density region of neutron stars is fairly well-known. The outer crust consists of a lattice of nuclei with free electrons and is a few 100 meters thick. The sequence of nuclei is controlled by their binding energies and follows mainly along the neutron magic numbers 50 and 82 (for a most recent investigation of the outer crust see [18]). Similar features will be discussed in the context of hypernuclei below. The inner crust starts at the neutron drip density at $n \approx 4 \cdot 10^{11}$ g/cm^3 and consists of a lattice of nuclei with free neutrons and electrons. The core starts at the end of the inner crust which occurs around half times normal nuclear matter density. In this core region, hyperons can populate the interior of neutron stars. The implications of the presence of hyperons for the properties of neutron star will be outlined in this review, which is an update and an extension of a preliminary version of Ref. [19].

2 Hyperons in Neutron Stars!

The term neutron star implies that the main component of neutron star matter are just neutrons. However, this picture changes drastically for matter at extremely high densities, i.e. in the core of neutron stars. Simple arguments for the presence of other more exotic species besides nucleons, electrons and muons can be given in terms of a free gas of hadrons and leptons. Matter in β-equilibrium but with no interactions starts to populate Σ^- hyperons already at $4n_0$, where n_0 is the normal nuclear matter density, the lighter Λ hyperons appear at $8n_0$ [20]. Inclusion of nuclear forces generically reduces these critical densities substantially, so that hyperons appear already around $2n_0$ (see e.g. [21] and references therein for the very first investigations of this kind).

That interactions are essential for the description of neutron star properties is evident from the fact that the corresponding equation of state of a free gas results in a maximum mass of only $M_{\rm max} \approx 0.7 M_\odot$ [22] which is by more than a factor two smaller than the presently most precisely known pulsar mass of $1.44 M_\odot$ for the pulsar PSR 1913+16. Hence, effects from strong interactions are crucial in describing neutron stars raising the maximum mass from 0.7 to two or more solar masses [23]. Note, that this is in contrast to white dwarfs which are basically stabilised by the Fermi pressure of the free electron gas only.

As hyperons are likely to be present in addition to nucleons, one has to consider the interactions between all stable baryons. Besides the nuclear force, there is some knowledge from hypernuclear physics about the interactions between hyperons and nucleons and scarcely between hyperons themselves. The ΛN interactions is very well studied, the potential depth of Λ hyperons is $U_\Lambda = -30$ MeV at $n = n_0$ (see e.g. [24]), so that bound Λ hypernuclear states exists. The situation is different for Σ hyperons. The only bound Σ hypernucleus known so far, ${}^4_\Sigma$He, is bound by isospin forces [25,26]. A detailed scan for Σ hypernuclear states turned out to give negative results [27]. The study of Σ^- atoms shows strong evidence for a sizable repulsive potential in the nuclear core, i.e. at $n = n_0$ [28,29,30]. A recent review on hadronic atoms can be found in [31] which confirms the repulsive nature of the nuclear Σ^- potential within a new geometric analysis of the Σ^- atomic data. On the other hand, the Ξ nucleon interactions seems to be attractive, several Ξ hypernuclear states are reported in the literature [32]. More recently, quasi-free production of Ξ's reveal an attractive potential of $U_\Xi = -18$ MeV [33,34] (with relativistic corrections, see [35]). Last but not least, the hyperon-hyperon (YY) interaction is not really well known, there are just a few double Λ hypernuclear events (for a recent review see [36]). The interaction between other pairs of hyperons as $\Lambda\Xi$ or $\Xi\Xi$ is not known at all experimentally. However, the hyperon potentials are essential for the determination of the composition of neutron star matter

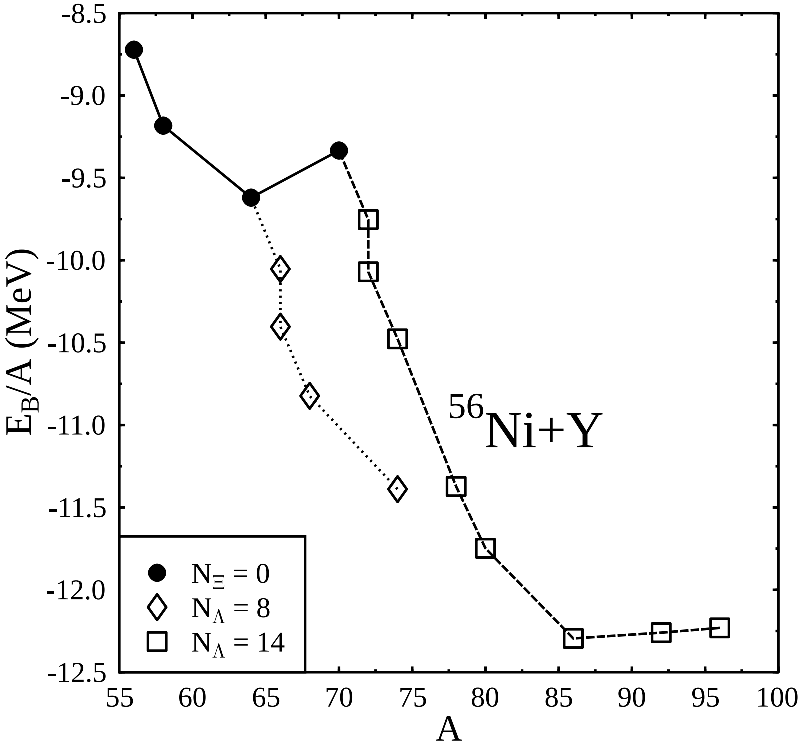

Fig. 1. The binding energy of strange hadronic matter for a nucleonic core of ^{56}Ni with added Λ and Ξ hyperons as a function of baryon number A (taken from [43]).

so basic hypernuclear data can provide substantial input for the modelling of neutron star matter.

Important for the stability of neutron stars is the short-range repulsion of the baryon-baryon interaction. Fits with nonrelativistic potentials to Λ hypernuclear data show effects from three-body interactions for the ΛN interaction [24]. The density dependence of the Schrödinger equivalent potential is compatible with the many-body mean-field potential of relativistic field-theoretical approaches and demonstrates that the hyperon potential turns repulsive above $2n_0$ [37]. The absence of these higher-order terms in density is likely to generate too soft an equation of state, so that the maximum mass of neutron stars falls below the mass limit of $1.44M_\odot$. Arguably, this might be the reason that modern many-body calculations of neutron star matter with nucleons and hyperons result in too low neutron star maximum masses [38,39,40,41]. Additional repulsion between hyperons and nucleons is needed. The hyperon three-body force has not received too much attention but is known for quite some time to be repulsive in nature for ΛNN [42] leading to the needed additional stability for neutron stars.

The appearance of hyperons in dense neutron star matter can be also elucidated by looking at finite systems of nucleons and hyperons, so called strange hadronic matter [44,43,45,35]. Let us consider an arbitrary number of nucleons and hyperons forming one big multi-hypernucleus. The system is stable against strong interactions, if reactions as $\Lambda+\Lambda \leftrightarrow \Xi+N$ and $\Sigma+N \rightarrow \Lambda+N$ are Pauli-blocked. The first reaction releases an energy of $Q \approx 25$ MeV, the second one $Q \approx 80$ MeV so that Σ hyperons can be hardly stabilised in hypernuclear systems. A similar feature will be present for neutron star matter, where it is indeed also likely that Σ hyperons do not appear (although the main reason is due to the repulsive potential for Σ hyperons). One can construct stable systems of nucleons and hyperons by adding successively Λ hyperons until Ξ hyperons can be populated as the filled Λ hypernuclear levels prevent the strong reactions by Pauli-blocking. Fig. 1 shows the binding energy of such Pauli-blocked systems for a nucleonic core of ^{56}Ni versus the baryon number. When the p-shell of the Λ hypernuclear level is filled up, Ξ hyperons can be added in the s-shell without loosing stability. The addition of hyperons leads to an overall increase in the binding energy as the hyperons populate deep lying s– and p– states in a separate quantum well. The nuclear binding energy with Λs and Ξs reaches up to $E/A = -12$ MeV (here a weak YY interaction is assumed)! In terms of the binding energy, it is energetically favoured to add hyperons to the system. A similar effect occurs for dense matter in β-equilibrium: here beyond some critical density, the filling of low-lying (with low Fermi momenta) hyperon states in a newly opened quantum well becomes preferred compared to adding more nucleons at large Fermi momenta. Hyperons appear in dense matter when their in-medium energy $\omega(Y)$ equals their chemical potential $\mu(Y) = \omega(Y) = m_Y + U_Y(n)$. Hyperons are then Pauli-blocked and can not decay as all levels are filled up for its possible decay products. In the case of neutron star matter, strange hadronic matter becomes now even stable to weak interactions!

In modern nuclear models, which are fitted to nuclear and hypernuclear data, hyperons appear in neutron star matter at $n \approx 2n_0$ in relativistic mean-field (RMF) models [46,47,48], in a nonrelativistic potential model [49], in the quark-meson coupling model [50], in relativistic Hartree–Fock models [51], in Brueckner–Hartree–Fock calculations [52,38,39,41], in chiral effective Lagrangians [53], in the density-dependent hadron field theory [54], and in G-matrix calculations [40]. It is remarkable that one of the very first calculations came to a similar conclusion [21]. Hence, neutron stars are indeed giant hypernuclei [46]!

The composition of neutron star matter depends sensitively on the assumed hypernuclear potentials. The Σ^- hyperon appears in dense matter usually together with the Λ at about $2n_0$, in some cases even slightly before the Λ due to its negative charge, if an attractive potential of $U_\Sigma = -30$ MeV similar to the Λ is chosen. However, for a repulsive potential the Σ^- as well as the other Σ hyperons will not be present in neutron star matter at all. Fig. 2 depicts the fraction of baryons and leptons as a function of density for a relativistic

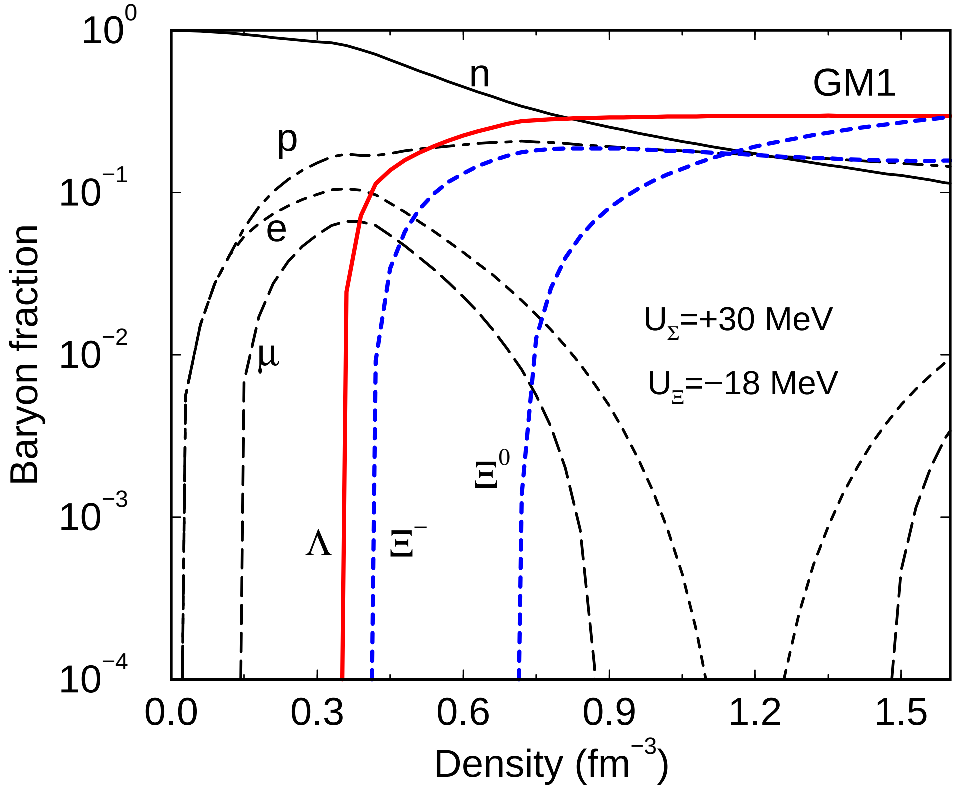

Fig. 2. The fraction of baryons and leptons in neutron star matter for a RMF calculation using set GM1 with weak hyperon-hyperon interactions (see [47]).

mean-field calculation using the parameter set GM1 [55] assuming a repulsive Σ potential. The Λ is present at $2.3n_0$, the Ξ^- hyperon at $2.7n_0$ (here the model with weak YY interaction is taken from [47]). Besides the Ξ^0 emerging at $4.7n_0$ no other hyperon is present up to $10n_0$, which is well beyond the maximum density reached for this equation of state. It is clear that hypernuclear data provides as an essential ingredient the hyperon potential depth which controls the composition in the core of neutron stars. The baryon and lepton population is highly sensitive to the in-medium potential of hyperons which will turn out to be important for the cooling of neutron stars.

3 Hyperons and cooling of neutron stars

Moderately aged neutron stars up to 1 million years after their formation will dominantly cool by volume emission of neutrinos. Cooling of photons from the surface will take over afterwards. The standard reaction for cooling is the modified URCA processes $N + p + e^- \to N + n + \nu_e$ and $N + n \to N + p + e^- + \bar{\nu}_e$ with a bystander nucleon to conserve energy and momentum. The modified URCA process is slow and leaves the neutron star quite warm until the photon cooling epoch. Much faster reactions are the direct URCA processes as $p + e^- \rightarrow n + \nu_e$ and $n \rightarrow p + e^- + \bar{\nu}_e$. However, these reactions can only proceed if the Fermi momenta fulfil the condition $p_F^p + p_F^e \geq p_F^n$. Charge neutrality implies $n_p = n_e$ or $p_F^p = p_F^e$, so that $2p_F^p \geq p_F^n$. Hence, the proton fraction has to exceed $n_p/n \geq 1/9 \approx 11\%$ for the direct nucleon URCA process to start. Relativistic calculations usually reach this value quite easily [56]. From Fig. 2 one can read off the critical density for the direct nucleon URCA process to be $1.5n_0$. Nonrelativistic calculations do not get that large proton fraction, as the asymmetry energy does not have the same strong density dependence as in relativistic models. In addition, nucleons are pairing strongly, so that energy is needed to break them up (recent reviews on cooling of neutron stars can be found in [17,57]).

On the other hand, hyperons can help substantially to cool a neutron star via the hyperon direct URCA processes as $\Lambda \rightarrow p + e^- + \bar{\nu}_e$ or $\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e$. Remarkably, the hyperon direct URCA processes happen immediately when hyperons are present and can also occur if there is no direct URCA process for nucleons allowed [58]! There is no minimum fraction of hyperons needed, as there is no additional constraint from the charge neutrality condition as for nucleons (in reality the presence of muons gives a small critical fraction of a few per mille, see [58]). Hence, if nucleons are gapped the most important cooling mechanism involves hyperons.

For weak YY coupling or interaction strengths, there will be rapid cooling due to the presence of hyperons mimicking some more exotic agent as kaon condensation or quark matter in the core. The rapid cooling process can start basically as soon as hyperons are part of the composition of neutron star matter, which implies that there is some critical neutron star mass for fast cooling. Hyperon cooling is only suppressed by hyperon pairing gaps which are presumably much smaller than the ones for nucleons. The importance of hyperon superfluidity for the hyperon direct URCA processes has already been pointed out in Ref. [59]. Hence, a detailed modelling of the cooling of neutron stars demands to have a knowledge not only on the composition, which is fixed by the in-medium potential of hyperons, but also on the YY interaction strength which determines the hyperon gap energy. There exist a few studies on hyperon cooling in the literature (see [60,61,62,63,64] and references therein). In the first hyperon cooling calculation with hyperon pairing [60], hyperons are present in the core for $M \geq 1.35M_\odot$. An attractive Σ nuclear potential was adopted so that the Σ^- appears even before the Λ. The dominant cooling process involves the reaction $\Sigma^- \rightarrow \Lambda + e^- + \bar{\nu}_e$. Two-body YY interactions were used as input to model the hyperon pairing gaps and their emissivities. It was found that hyperon gaps improve the thermal history and are more consistent with x-ray observations of neutron stars. On the other hand, in a subsequent study [61] the Λ hyperon appeared at a slightly lower density than the Σ^-, so that there was a tiny density range of unpaired Λ hyperons present. These unpaired hyperons resulted in even faster cooling for heavier stars via the hyperon direct URCA. Also, new improved hyperon-nucleon interactions find very large pairing gaps for the Σ hyperons which would suppress the hyperon direct URCA processes involving Σ hyperons, see e.g. [62]. However, note that cooling processes with Σ hyperons are likely to be not present anyway for a repulsive Σ nuclear potential as the Σ hyperons would not be part of the neutron star matter composition. The conclusion is, that indeed two-body forces between hyperons and nucleons have an enormous impact on the cooling history of neutron stars. Hence, hypernuclear physics serves as a key ingredient not only for the composition of dense neutron star matter but also for the cooling history of neutron stars.

4 Hyperons and the maximum mass of neutron stars

It is known for quite some time, that hyperons have a significant effect on the global properties of compact stars. As new degree of freedom, which can populate new Fermi levels, hyperons can lower the overall Fermi energy and momentum of baryons and leptons. Thereby, the total pressure of the system for a given energy density is considerably lowered, which implies that the equation of state is substantially softened.

The first consistent implementation of the relativistic Λ hyperon potential depth in neutron star matter was performed by Glendenning and Moszkowski [55] using a relativistic field theoretical approach. The other hyperon potentials were fixed by assuming universal coupling strengths for all hyperons by setting the Σ and Ξ hyperon coupling constants equal to the one of the Λ. Hence, hypernuclear constraints for Σ and Ξ hyperons were not taken into account, in particular the Σ potential is as attractive as that of the Λ. Follow-up calculations adopt SU(3) symmetry for the vector coupling constants and specify the scalar coupling via the different hyperon potentials, see [47]. The neutron star sequence with nucleons and leptons only reached a maximum mass of $M \approx 2.3 M_\odot$. A substantial decrease of the maximum mass occurred once hyperons were taken into account, with parameters fixed by hypernuclear data. The maximum mass for such "giant hypernuclei" turned out to be now around $M \approx 1.7 M_\odot$. Moreover, they demonstrated that the case of noninteracting hyperons results in a too low maximum mass, i.e. $M < 1.4 M_\odot$! Clearly, strong (repulsive) interactions between hyperons have to be implemented for a consistent description of pulsar masses.

The issue of the softness of the nuclear equation of state and the maximum mass of neutron stars has received considerable renewed interest recently due to the analysis of heavy-ion data. The focus will be here on the analysis of strange particle production in heavy-ion collisions, in particular the subthreshold production of kaons measured by the KaoS collaboration [65,66] at GSI, Darmstadt. The ratio of the multiplicities per baryon of the produced kaons in C+C and in Au+Au collisions turns out to be rather insensitive to the underlying microphysical input for the transport simulation, as the kaon-nucleon optical potential, cross sections, lifetime of resonances etc. The analysis of the data at different bombarding energies with transport simulations arrives at the conclusion that the nuclear equation of state should be rather soft at densities around $2 - 3n_0$ [67,68,69,70]. The extracted compression modulus turns out to be around 200 MeV for a simple Skyrme-type parameterisation of the nuclear equation of state.

However, as outlined above, most recent pulsar data points towards quite large masses or large radii which can be only reconciled with a rather stiff nuclear equation of state. There seems to be a conflict between heavy-ion data and pulsar observations which can be resolved actually, see Refs. [71,72]. First, transport models use actually the Schrödinger equivalent potential as input not the nuclear equation of state. Second, the nuclear density ranges probed are different for the production of kaons and the maximum mass of neutron stars. Typically, the maximum central density reached in the center of neutron stars amounts to about $(5 - 6)n_0$, which depends on the assumed nuclear model. These values could be much larger. However, one hardly finds a calculation in the literature with substantially lower values for the maximum central densities. As stated above, kaon production in heavy-ion collisions is sensitive up to $2.5n_0$. Therefore, there is a gap in the nuclear density regions probed. The stiffness of the hadronic equation of state above $2.5n_0$ controls the value of the maximum mass achievable for neutron stars. Interestingly, this is the density regime where hyperons presumably appear and modify the neutron star matter properties significantly. These lines of arguments have been cross-checked in a more detailed investigation using Skyrme-type and relativistic mean-field models [71,72]. The 'soft nuclear equation of state' extracted from heavy-ion data is indeed compatible with the recent pulsar mass measurements when only nucleons and leptons are considered as the basic constituents in neutron star matter. The inclusion of hyperons, however, causes an equation of state which turns to be very soft at high densities with the constraint from heavy-ion data. The maximum mass reached for several nuclear equations of state analysed within the relativistic mean-field model is just $M = 1.53M_\odot$ [72]. If a more massive neutron star is confirmed, the role of hyperons in neutron stars in combination with the constraint from heavy-ion data needs to be reinvestigated.

Again, hyperons play a decisive role in compact star physics. The feature, that hyperons lower drastically the maximum mass of neutron stars became even more pronounced with modern many-body approaches to neutron star matter beyond the mean-field approximation. In relativistic Hartree-Fock calculations, the maximum mass of neutron stars was computed to be $M_{\max} = (1.4 - 1.8)M_\odot$ depending sensitively on the chosen hyperon coupling strength

[73]. In Brueckner-Hartree-Fock approaches using Nijmegen soft-core hyperon-nucleon (YN) potentials maximum masses of $M_{\rm max} = 1.47 M_\odot$ have been derived for the nucleon-nucleon and YN interactions only and $M_{\rm max} = 1.34 M_\odot$ when including the YY interactions [39]. In the same approach, three-body forces for nucleons have been included but none for the hyperons so that a maximum mass of only $M_{\rm max} = 1.26 M_\odot$ was attained [38]. The latter maximum masses are even below the mass limit of the Hulse-Taylor pulsar of $1.44 M_\odot$ and the corresponding hyperonic equations of state are clearly ruled out by pulsar data. Obviously, some additional hyperon physics is missing in those cases. Presumably, three-body forces for hyperons will solve this problem, as they are repulsive and will raise the maximum mass (some crude investigations in this directions can be found in [40] supporting this statement). Here, input is needed from hypernuclear physics, not only for the hyperon three-body force but also for the momentum dependence of the hyperon interactions, as dense matter probes momenta of the order of several hundred MeVs. Contrary to the widely used standard mean-field and nonrelativistic approaches, Brueckner-type approaches adopt momentum-dependent potentials which have to be fixed by YN scattering and hypernuclear data.

The YY interaction is another important ingredient for the description of neutron star matter. In fact, it is even possible to generate a new class of compact stars, hyperon stars, besides ordinary white dwarfs and neutron stars, by a new stable solution of the Tolman-Oppenheimer-Volkoff equation [74]. By increasing the overall strength of the YY interactions (in particular the unknown $\Xi\Xi$ interaction which can be probed in heavy-ion collisions however, see [75]), a first order phase transition appears from neutron matter to hyperon-rich matter. A mixed phase is present for a wide range of densities $n_{\rm mix} = (2.5 - 6.5) n_0$. Interestingly, all hyperons (Λ, Ξ^0, Ξ^-) appear at the start of the mixed phase, as the bubbles of the new hyperon phase are charged and have a larger density than the surrounding normal neutron matter (note that for a Gibbs construction the chemical potentials must be equal in phase equilibrium, not the densities). The strong first order phase transition due to hyperons has a strong impact on the mass-radius relation for compact stars. A new stable solution in the mass–radius diagram appears, as the curve reaches a second maximum for the mass for small radii. Those hyperon stars are generated via attractive YY interactions (mainly $\Xi\Xi$ interactions). We note that a weak $\Lambda\Lambda$ does not rule out a strong $\Xi\Xi$ interaction nor the possible existence of hyperon stars. Within the Nijmegen soft core model NSC97, the hyperon-hyperon interactions are highly attractive in certain channels [76]. Even a bound $\Xi\Xi$ state was found. However, other bound states also appear in the NSC97 model which are now considered to be fictitious. The new Nijmegen potential ESC04 [77,78] has not been extended to the $S = -4$ sector so far, unfortunately. In a recent SU(6) quark model calculation, which derived the baryon potentials for the full baryon octet, no bound $\Xi^0\Xi^0$ state has been found [79].

The two different solutions for hyperon-rich matter behave like neutron star twins: they have similar maximum masses, $M_{\rm hyp} \sim M_n$, but different radii $R_{\rm hyp} < R_n$. In addition, selfbound compact stars for strong YY attraction with $R = 7-8$ km are also possible, but demand that strange hadronic matter is absolutely stable so that ordinary neutron stars are completely converted to hyperon stars. Such neutron star twin solutions have been also found for a strong first order phase transition to quark matter [80,81,82]. In fact, any strong first order phase transition can produce a so-called third family of compact stars. Signals for such a strong phase transition can be detected by direct mass and radius measurements, or by the collapse of a neutron star to the third family via measurements of gravitational waves, γ-rays, and neutrinos.

In passing, I note that strange multiquark states can also exist in neutron stars, as the H-dibaryon [83] or strange pentaquarks [84]. Pentaquarks in neutron star matter will further reduce the maximum mass, which is being sensitive to the Θ^+ potential. The pentaquark Θ^+ appears around $4n_0$ for a potential depth of $U(\Theta^+) = -100$ MeV at n_0. For the maximum mass star the Θ^+ population amounts to 5% in the core. Present confirmed pulsar mass limits, however, do provide a very weak constraint on Θ^+ potential (e.g. for $M > 1.6M_\odot$, the potential depth should $U(\Theta^+) > -190$ MeV) which are a much stronger for a hypothetical negatively charged Θ^-.

5 Hyperons and Gravitational Wave Emission

There is an astonishing connection between microscopic reactions involving hyperons and the overall stability of rotating neutron stars with respect to gravitational wave emission. As pointed out by Jones [85,86] the *dominant* contribution to the bulk viscosity of neutron star matter originates from non-mesonic weak decay reactions of hyperons in the dense medium, not from purely nucleonic reactions. In particular the reaction $\Lambda + p \to n + p$ [87], and to some extent the reaction $\Sigma^- + p \to n + n$ [88], control the overall bulk viscosity important for the r-mode instability of rotating neutron stars. The oscillating neutron star is out of weak equilibrium and is readjusted by those weak reactions back to equilibrium. The nonmesonic weak hyperon decays are able to stabilise the rotating neutron star in a broader region in the temperature-period diagram than the standard weak processes for nucleons only. If the neutron star is unstable with respect to the r-modes, it will emit gravitational waves. Therefore, the knowledge on the weak nonmesonic reaction rates is crucial for determining the stable regimes of rotating neutron stars. In addition, two-body interactions with hyperons and the size of pairing gaps need to be known to check for hyperon superfluidity which will substantially change the bulk viscosity. Improved calculations of the hyperon bulk viscosity have been performed in [89]. Applications to hybrid stars, compact stars with quark matter in the core, including the effects from hyperons have been studied in [90]. It was demonstrated that hyperons are very important even for the stability of hybrid stars with respect to gravitational wave emission. In certain cases, it seems possible that accreting rotating neutron stars persistently emit gravitational waves [91]. Even the effect of hyperon-hyperon interactions on the r-mode stability were investigated [92].

The weak nonmesonic decays $\Lambda + N \to N + N$ have been studied in medium to heavy hypernuclei as it is the main decay channel (for reviews see [93,94]). There was a long-standing puzzle of the branching ratio of proton- and neutron-induced weak hyperon decays, which was solved by a careful analysis of two- and three-body processes, see [95]. The new hypernuclear data on their weak decays indicate that the proton-induced weak decay, which is studied for the r-modes of pulsars, is the main decay channel. However, the neutron-induced one is nearly equally strong and is usually neglected for the calculation of the bulk viscosity of neutron star matter. Also, other nonmesonic processes appear in hyperon star matter as $\Lambda + \Lambda \to \Lambda + n$ which will be determined by the future double Λ hypernuclear experiments. The measurement of the weak nonmesonic decay for $S = -2$ systems is also important to test the SU(3) symmetry of the weak matrix elements. The standard ansatz fails in describing the weak decay amplitudes of hyperons in the vacuum and a more general SU(3) scheme is needed [75]. It would be interesting to test this symmetry pattern for branching ratios of double-hypernuclei and to explore the relation to the stability of pulsars with respect to gravitational wave emission.

There is already some astrophysical data available on the gravitational wave emission from pulsars. Oscillations with a frequency of 1122 Hz have been observed for an accreting x-ray binary [96]. If this is the rotation frequency of the neutron star, then exotic matter must be present inside with a suitable bulk viscosity stabilising the rotating neutron star [97]. The LIGO collaboration has set new limits on the gravitational wave emission from 78 pulsars, rotation-powered neutron stars, which are getting close to the spin-down limit [98] and which will be improved considerably in the near future.

6 Summary

Hyperons have a substantial impact on neutron star properties. There is a sizable decrease in the maximum mass of neutron stars due to the presence of hyperons in the core. The Λ hyperons appear at $n \approx 2n_0$ in neutron star matter. The population of Σ hyperons hinges crucially on their in-medium potential. They are likely to be absent for a repulsive potential, but the negatively charged Σ^- could be the first exotic component in neutron star matter for an attractive potential. A tiny amount of hyperons can suffice to cool neutron stars rapidly by the hyperon direct URCA process, which is controlled by hyperon pairing gaps. A strongly attractive YY interaction, between Ξ hyperons, results in a first order phase transition from neutron-rich to hyperon-rich matter. This transition allows for a new, stable solution for compact stars, hyperon stars, with similar masses but smaller radii. The presence of the nonmesonic weak decay reactions with hyperons in neutron stars determines the bulk viscosity of neutron star matter and leads to an enhanced stability window with regard to r-modes of pulsars.

It is obvious, that hypernuclear physics provides essential input for compact star physics. The YN interactions, in particular the potential depth in bulk nuclear matter, controls the population of hyperons for massive neutron stars, the first exotic component likely to appear for supranuclear densities present in the core. The emergence of hyperons softens the nuclear equation of state and the maximum neutron star mass possible considerably which depends on the YN coupling strength and sensitively on the hyperon three-body forces. Two-body YY interactions regulate the cooling behaviour of massive neutron stars, as the hyperon direct URCA reaction is suppressed by hyperon gaps. Nonmesonic weak decay of hyperons in the dense medium as well as hyperon superfluidity controls the bulk viscosity of neutron star matter which regulates the stability of r-modes of pulsars and the emission of gravitational waves. In addition, hyperons can generate a new class of compact stars, hyperon stars, for a suitably attractive YY potential. The ongoing and future experimental hypernuclear programs at DAΦNE, Jefferson Lab, KEK, J-PARC, MAMI-C, and at GSI, Darmstadt, in particular the HypHI program and HYPERGAMMA with PANDA at FAIR, will provide here the decisive inputs for addressing the macrophysics and microphysics of neutron stars as hyperons play such an important role for many compact star observables.

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