# Strangeness in Compact Stars $\overline{x}$

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#### **Abstract**

We discuss the impact of strange hadrons, in particular hyperons, on the gross features of compact stars and on core-collapse supernovae. Hyperons are likely to be the first exotic species which appears around twice normal nuclear matter density in the core of neutron stars. Their presence largely influences the mass-radius relation of compact stars, the maximum mass, the cooling of neutron stars, the stability with regard to the emission of gravitational waves from rotationpowered neutron stars and the possible early onset of the QCD phase transition in core-collapse supernovae. We outline also the constraints from subthreshold kaon production in heavy-ion collisions for the maximum possible mass of neutron stars.

*Keywords:* Hypernuclei, Nonmesonic Weak Decay, Strange Hadronic Matter, Neutron Stars, Maximum Mass, Cooling of Neutron Stars, R-Mode Instability, Gravitational Waves, Supernovae, Heavy-Ion Collisions, Nuclear Equation of State *PACS:* 21.80.+a, 26.60.-c, 97.60.Jd, 12.39.Mh, 21.65.Cd, 25.75.-q

# **1. Introduction**

Neutron stars constitute a fantastic laboratory for studying matter under extreme conditions. In particular in the core of neutron stars, new exotic phases could be present with considerable impacts on its evolution and global properties. The focus of the following discussion will be on the presence of hyperons being a major component of the composition of neutron star matter at high densities which is largely based on the recent review [\[1](#page-6-0)].

The maximum masses of neutron stars are controlled by the stiffness of the nuclear equation of state which is related to the three-body force involving hyperons. The subthreshold production of kaons in heavy-ion collisions provide a new limit on the maximum possible mass of neutron stars which just relies on the nuclear equation of state, as constraint by the heavy-ion data, up to a fiducial density and causality arguments. The cooling of neutron stars for up to about a million years is governed by the emission of neutrinos. Here the weak processes involving hyperons allow for fast cooling depending on the size of the hyperon gap, i.e. the two-body interaction

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between hyperons. Rotating neutron stars can emit gravitational waves due to the presence of the so called r-mode instability which is highly sensitive to the viscosity of dense matter. Nonmesonic weak processes with hyperons turn out to be a decisive ingredient for the viscosity and therefore for the stability of rotation-powered neutron stars, in particular for hot proto-neutron stars or accreting binary rotation-powered neutron stars. As hyperons appear at moderate densities, about twice normal nuclear matter density for cold neutron star matter, they are present to some amount also in hot supernova matter shortly after the bounce. Fluctuations can trigger then more easily the nucleation process for forming bubbles of strange quark matter thereby enabling the onset of the QCD phase transition much earlier in the evolution of the supernova, maybe already shortly after the bounce. A first order phase transition present during the first second of a core-collapse supernova has profound implications for the overall evolution of the supernova, the neutrino signal and possibly for the r-process nucleosynthesis in the neutrino wind of the proto-neutron star.

# **2. Observations of neutron stars**

Neutron Stars are extremely compact, massive objects with typical radii of  $\approx 10$  km and typical masses of  $1 - 2M_{\odot}$ . Hence, extreme densities have to be present in the core of a neutron star, which must be several times nuclear density  $n \gg n_0 = 3 \cdot 10^{14}$  g/cm<sup>3</sup>. Masses of pulsars can be determined to quite some precision by the observation of binary pulsars, i.e. rotation-powered neutron stars with a companion which is either a normal star, a white dwarf or even another neutron star.

The best determined mass of  $M = (1.4414 \pm 0.0002)M_{\odot}$  for the Hulse-Taylor pulsar [\[2\]](#page-6-1) still constitutes the most massive known neutron star mass which is well known and relies just on post-Keplerian analysis of the orbital parameters (note that the mass of PSR J0751+1807 has been corrected from  $M = (2.1 \pm 0.2)M_{\odot}$  to  $M = (1.14 - 1.40)M_{\odot}$  [\[3](#page-6-2)]). A new measurement of the pulsar PSR J1903+0327 arrives at a mass of  $M = (1.67 \pm 0.01) M_{\odot}$  [\[4,](#page-6-3) [5](#page-6-4)] but the improved mass measurement is not finalized yet.

Constraints on the mass-radius relation (see e.g. [\[6\]](#page-6-5) for a review) can be derived from the spin rate from PSR B1937+21 of 641 Hz which gives a radius of  $R < 15.5$  km for  $M = 1.4 M_{\odot}$ The causality limit for the nuclear equation of state with *R* > 3*GM* bounds the range for the possible mass-radius relation from the other side, so that a distorted pie-like region remains. We stress that any further constraint on the mass-radius relation of neutron stars discussed so far in the literature is liable to suffer from particular model assumptions, so we refrain from discussing them here and refer to the above mentioned review.

## **3. Composition of Neutron Stars**

The structure of a neutron star in the core is not known at present. Several scenarios have been discussed in the literature as e.g. the formation of a pion condensed phase, kaon condensation, the transition to strange quark matter and the possibility of having pure strange quark stars (for a review see [\[7](#page-6-6)]). We will argue in the following that the first exotic phase which appears in the core of neutron stars is likely to be hyperonic in nature.

The general critical condition for the presence of any particle in equilibrated cold matter is that the chemical potential of the particle equals its in-medium energy (note that this assumes that one can adopt a quasi-particle picture). Neutron star matter is in  $\beta$ -equilibrium, so that all

Hadron	n.n		others
appears at: $  \ll n_0   4n_0   8n_0   > 20n_0$			

<span id="page-2-0"></span>Table 1: The critical density for the appearance of hadrons in neutron star matter for a free gas. Hyperons are present at  $4n_0$  but no pion or kaon condensation is formed for densities below  $20n_0$ .

weak decays are Pauli-blocked. Hence, neutrons and hyperons, if present, can not decay by weak interactions as in free space. For boson condensation (in the s-wave) of  $\pi^-$  and  $K^-$  the critical condition reads  $E_b = \mu_b = \mu_e$ . For a free gas of electrons, muons and hadrons one finds in table [1](#page-2-0) that the  $\Sigma^-$  is the first strange hadron which is present at high densities appearing at  $4n_0$ , followed by the  $\Lambda$  at 8*n*<sub>0</sub> [\[8\]](#page-6-7). The  $\Sigma^-$  is favoured due to its negative charge which balances the positive charge of the protons and helps to reduce the Fermi energy of the electrons. Note that all other hadrons, as the  $\Sigma^+$ , the  $\Xi^-$ , the  $\pi^-$  or the  $K^-$  are not part of the composition for any reasonable nuclear density,  $n < 20n_0$ . Note that interactions will considerably change the critical density for the onset of a species. But the corresponding equation of state results in a maximum mass of only  $M_{\text{max}} \approx 0.7 M_{\odot} < 1.44 M_{\odot}$  [\[9](#page-6-8)] which implies that effects from strong interactions are essential to describe pulsar data and therefore the gross features of neutron stars.

There have been numerous models being utilized to determine the onset of hyperons in neutron star matter. If these models are properly adjusted to the available hypernuclear data, they find consistently that hyperons appear around  $n \approx 2n_0$ . Such investigations include relativistic mean-field models [\[10](#page-6-9), [11](#page-6-10), [12](#page-6-11), [13](#page-6-12)], the nonrelativistic potential model [\[14\]](#page-6-13), the quark-meson coupling model [\[15\]](#page-6-14), the relativistic Hartree–Fock approach [\[16](#page-7-0)], Brueckner–Hartree–Fock calculations [\[17,](#page-7-1) [18](#page-7-2), [19,](#page-7-3) [20](#page-7-4)], chiral effective Lagrangians using SU(3) symmetry [\[21,](#page-7-5) [22](#page-7-6), [23\]](#page-7-7), the density-dependent hadron field theory [\[24](#page-7-8)], G-matrix calculations [\[25](#page-7-9)] and the renormalization group approach with a  $V_{\text{low k}}$  potential for hyperons [\[26\]](#page-7-10). Hence, most likely neutron stars are giant hypernuclei [\[10\]](#page-6-9)!

The composition of neutron star matter is largely controlled by the hyperon potential depths which are fixed to the available hypernuclear data and hadronic atom data. For an attractive potential of the Σ hyperons, the  $\Sigma^-$  can appear even before the Λ in dense matter. But if the Σ-nucleon potential is repulsive at normal nuclear matter density, then the Σ hyperons are not populated at all, only the As are present in matter around  $n = 2n_0$ , the  $\Xi^-$  before  $n = 3n_0$ . Therefore, the hyperon population is highly sensitive to the in-medium potential.

#### **4. Masses of Neutron Stars**

Hyperons can also play a crucial role for the maximum mass of neutron stars, which is controlled by the high-density equation of state. The more new particles emerge at high densities, the more can the Fermi energy be lowered for a given number density which results in a lowered Fermi pressure for a given energy density for nonrelativistic particles. Note that this argument can not be applied to completely new phases as e.g. the chirally restored phase (quark matter).

The first discussion of the implication for the maximum mass of neutron stars with hyperons which takes into account correctly the hyperon potential depths in dense matter is given in [\[27\]](#page-7-11) within the relativistic mean-field model. While the maximum mass of neutron stars with nucleons and leptons only is about  $M \approx 2.3 M_{\odot}$ , it drops substantial due to hyperons. The maximum mass for "giant hypernuclei" reads only  $M \approx 1.7 M_{\odot}$ , noninteracting hyperons result in a too low mass



Figure 1: The composition of neutron star matter as a function of baryon density. Hyperons appear around 2*n*<sub>0</sub>. The presence of the Σ hyperons depends crucially on the sign of the hyperon-nucleon potential, there are no Σ hyperons present for a repulsive potential. Left plot: attractive Σ potential, right plot: repulsive Σ potential (see [\[13](#page-6-12)] for the details of the model used).

of  $M < 1.4M_{\odot}$  which is incompatible with observations. Hence, at high densities repulsive interactions between hyperons and nucleons are important for the stability of neutron stars.

Modern many-body approaches use as input the two-body potentials as deduced from hyperonnucleon scattering data. For the Nijmegen soft-core hyperon nucleon potentials Vidana et al. find that the maximum mass is only  $M_{\text{max}} = 1.47M_{\odot}$  which reduces to even  $M_{\text{max}} = 1.34M_{\odot}$ when the hyperon-hyperon potentials are switched on [\[19\]](#page-7-3). Also Baldo et al. find values of  $M_{\text{max}} = 1.26 M_{\odot}$  even when including three-body nucleon interactions [\[18\]](#page-7-2). More recently Schulze et al. [\[20](#page-7-4)] and Djapo et al. [\[26\]](#page-7-10) confirm that  $M_{\text{max}} < 1.4 M_{\odot}$  for modern microscopic (ab initio) approaches. Hence, the neutron star equation of state gets too soft at high densities giving too low masses. Probably the underlying reason are missing three-body forces for hyperons (YNN, YYN, YYY), which give additional repulsive contributions at high densities. If so then it seems that neutron stars can not live without hyperon three-body forces. A solution to this problem of the modern many-body approaches has been discussed in detail in ref. [\[28\]](#page-7-12) where it was shown that the presence of quark matter in the core stabilizes the compact star resulting in much larger maximum masses. But certainly, also more input is needed from hypernuclear physics by e.g. the study of light double hypernuclei in the near future to extract the hyperonic three-body forces.

#### **5. Maximum possible mass of neutron stars**

There is another strange hadron with strong relations to the physics of the maximum possible mass of neutron stars. Kaons produced subthreshold in heavy-ion experiments can serve as a messenger of the high-density zone created in the collision. Kaons are produced by associated production e.g. via NN $\rightarrow$  NAK, and NN $\rightarrow$ NNKK in elementary proton-proton collisions. In the medium, i.e. in heavy-ion collisions, rescattering processes open up as  $\pi N \to \Lambda K$ ,  $\pi \Lambda \to$  $N\overline{K}$  from produced pions which have a lower q-value and are therefore able to pump up the kaon production rates substantially compared to the elementary pp-collisions. At subthreshold bombarding energies of heavy ions the matter can be compressed up to  $3n_0$ . However, kaons have a long mean-free path, they scatter elastically with nucleons and pions, only hyperons can absorb them as kaons carry an antistrange quark. Hence, kaons can escape from the high density zone unimpeded, their production rates will be controlled by the amount of compression achieved in the central region of the collision. For a recent review of the relation between the nuclear equation of state and kaon production rates in heavy-ion collisions see [\[29\]](#page-7-13).

The KaoS collaboration has measured kaon production  $(K^+)$  in heavy-ion collisions at subthreshold energies [\[30,](#page-7-14) [31\]](#page-7-15). They used carbon-carbon collision as a control experiment to assess the medium effects in comparison to heavy-ion collisions with gold-gold collisions at 0.8 AGeV and 1.0 AGeV. The multiplicity per mass number for Au+Au collisions relative to the one for C+C collisions turns out to be rather insensitive to input parameters in numerical simulations as effects from two-body interactions, cross sections, and in-medium potentials effectively cancel out [\[32,](#page-7-16) [33\]](#page-7-17). A strong increase of the kaon production rate was seen towards lower collision energies which could only be matched by transport calculations with a soft nuclear equation of state, here characterized by a compression modulus of  $K_N \approx 200$  within a simple Skyrme parametrization.

These findings can now be utilized for constraining the maximum possible mass of neutron stars using causality arguments. Let us assume that we know the nuclear equation of state up to some fiducial density  $\epsilon_f$ . Then the neutron star matter can not be stiffer than the causality limit which is  $p = \epsilon$  above that fiducial density as shown by Rhoades and Ruffini [\[34](#page-7-18)]. Hence, there is a maximum mass possible which is related to the fiducial density by  $M_{\text{max}} = 4.2 M_{\odot} (\epsilon_0 / \epsilon_f)^{1/2}$ , where  $\epsilon_0$  is the energy density of nuclear matter at saturation (see e.g. [\[35](#page-7-19)] who are using a nuclear equation of state derived from fits to nuclei and low-energy nucleon-nucleon scattering data). As the new constraint on the nuclear equation of state as determined from the analysis of the KaoS data concerns densities above normal nuclear matter density, the limit on the maximum mass can be lowered accordingly by increasing the fiducial density to  $\epsilon_f \approx 2\epsilon_0$  [\[36,](#page-7-20) [37\]](#page-7-21) arriving at a new upper mass limit of about  $2.7M_{\odot}$  from heavy-ion data.

### **6. Weak Hyperonic Reactions and Neutron Stars**

A neutron stars cools most efficiently by emitting neutrinos for the first million years after being created in a core-collapse supernova. The modified URCA process occurs at finite density and is slow as it needs a bystander nucleon to conserve energy and momentum:  $N + p + e^- \rightarrow$  $N + n + v_e$  and  $N + n \rightarrow N + p + e^- + \bar{v}_e$ . Without a bystander nucleon, the so called direct URCA process is much faster due to the increased phase space:  $p + e^- \rightarrow n + v_e$  and  $n \rightarrow p + e^- + \bar{v}_e$ but can only proceed for *p p*  $P_F^p + P_F^e \geq P_F^n$  to conserve energy and momentum. As charge neutrality implies that  $n_p = n_e$  the proton fraction must be at least  $n_p/n \geq 1/9$  so that the nucleon URCA process is only allowed for large proton fractions. On the contrary the hyperon URCA process as  $\Lambda \to p + e^- + \bar{\nu}_e$  and  $\Sigma^- \to n + e^- + \bar{\nu}_e$  happen immediately when the respective hyperons are present. These reactions enable fast cooling and are only suppressed by hyperon pairing gaps. Cooling with hyperons has been studied in refs. [\[38](#page-7-22), [39,](#page-7-23) [40](#page-7-24), [41,](#page-7-25) [42](#page-7-26)] where two-body hyperonhyperon interactions were used as input for the calculations of the neutron star cooling rates. Pairing of  $\Sigma$  hyperons for cooling processes in neutron stars were studied by Vidana and Tolos in [\[40\]](#page-7-24). Generically, the cooling depends crucially on the composition of the neutron star, in particular whether or not hyperons are present which will be the case beyond a certain critical neutron star mass. To really assess the role of hyperons for the cooling mechanism of neutron stars one needs to know also the neutron star mass. Unfortunately, up to now the masses have

not been determined for those nearby and young neutron stars where the luminosity in x-rays has been measured and constraints on the cooling curves could be extracted.

There is another effect which is dominantly controlled by weak reactions involving hyperons: the gravitational wave emission from rotating neutron stars by the so called r-mode instability [\[43,](#page-7-27) [44,](#page-7-28) [45](#page-7-29), [46,](#page-7-30) [47,](#page-7-31) [48](#page-7-32), [49](#page-7-33), [50,](#page-7-34) [51,](#page-7-35) [52](#page-7-36)]. Oscillations of the neutron star brings the matter out of  $\beta$ -equilibrium, as there are overdense and underdense regions. The dominating effect to restore equilibrium is by weak nonmesonic processes of the kind  $NN \leftrightarrow \Delta N$  and  $NN \leftrightarrow \Sigma N$ . Strong reactions are faster but they can not change strangeness to reestablish weak equilibrium in the neutron star material. If those weak reactions are not taken into account, the neutron star can not damp the oscillations, has to emit gravitational waves and slows down. This feature creates an instability window for certain combinations of the temperature and rotation frequency of the star. The key ingredient for the stability relative to the emission of gravitational waves is the viscosity which depends crucially on hyperon weak nonmesonic reactions. If hyperons are gapped these reactions are suppressed, so that the hyperon-hyperon interactions play again an important role, see also [\[51](#page-7-35)]. Recently, the LIGO collaboration has published new limits on the gravitational wave emission from the Crab pulsar which are well below the spin-down limit and constrain already the amount of energy which can be emitted by gravitational waves substantially [\[53\]](#page-7-37).

# **7. Hyperons and the QCD phase transition in supernovae**

Finally, we address the importance of hyperon populations for the QCD phase transition in core-collapse supernova explosions. Stars with a mass of more than eight solar masses end in a core-collapse supernova. In recent years new generations of simulation codes have been developed which includes multidimensional treatments and improved approximations for the neutrino transport. Still, the shock front stalls and can only be reinvigorated by neutrino heating for low progenitor masses. The underlying mechanism for massive progenitor stars to explode has not yet fully agreed upon and several mechanism have been proposed as e.g. the standing accretion shock instability (for a review see [\[54\]](#page-7-38)).

Hyperons can also be present in supernova matter as densities above saturation densities and temperatures of about 20 MeV are achieved shortly after the bounce. A supernova matter equation of state with hyperons has been studied by Ishizuka et al. [\[55](#page-7-39)] recently. For a proton fraction of  $Y_p = 0.4$  and a temperature of 20 MeV the population of hyperons reaches about 0.1%. Net strangeness is produced thermally as hyperons are in weak equilibrium. The presence of hyperons softens the nuclear equation of state, so that the recollapse of massive progenitor stars of  $100M_{\odot}$  to a black hole is triggered [\[56\]](#page-7-40).

Fluctuations in the hyperon abundances help to form local regions with a high strangeness content. Then, it is much more feasible to nucleate those regions to strange quark matter directly than to normal quark matter as demonstrated by Mintz et al. [\[57](#page-7-41)]. Therefore, the presence of hyperons catalyzes substantially the production of strange quark matter bubbles allowing for the onset of the QCD phase transition in supernova matter. The conditions in supernovae are favourable for the QCD phase transition to occur: quark matter appears at much lower density due to weak equilibrium, the low critical density for low proton fractions due to the nuclear symmetry energy and the finite temperature. For the situation in heavy-ion collisions, the phase transition line at low temperatures and high baryochemical potentials is located at much higher densities as there is no weak equilibrium so that normal quark matter has to be produced initially and due to the isospin-symmetric matter present. Hence, for the supernova matter at bounce with  $T = 10 - 20$  MeV,  $Y_p = 0.2 - 0.3$ ,  $\epsilon = (1 - 1.5)\epsilon_0$  production of quark matter in supernovae at

bounce seems to be feasible [\[58\]](#page-7-42) without any contradiction to heavy-ion data. The implications of an early onset of the QCD phase transition for core-collapse supernovae are that a second shock wave is produced which releases a second burst of antineutrinos when the shock front is running over the neutrinosphere [\[59\]](#page-7-43). The neutrino signal of the phase transition shows up in the temporal profile of the emitted neutrinos from the supernova. There is a pronounced second peak of anti-neutrinos due to the formation of quark matter whose peak location and height is determined by the critical density and strength of the QCD phase transition [\[59](#page-7-43)].

## **8. Summary**

Hypernuclear physics has a substantial impact on neutron star properties. Two-body hyperonnucleon interaction controls the composition of neutron star matter. Hyperons are most likely the first exotic phase to appear in the core around twice normal nuclear matter density. Hyperons can pair and form superfluids or superconducting phases. The three-body hyperon-nucleon and hyperon-hyperon forces are important for the maximum mass of neutron stars. Only low maximum masses below  $1.4M_{\odot}$  are found in modern approaches without the hyperonic three-body force. Kaon production in heavy-ion collision are a probe of the nuclear equation of state at subthreshold energies. The experimental data sets a new upper limit on the maximum mass allowed by causality. Nonmesonic weak reactions with hyperons are crucial for the cooling history of young neutron stars as hyperons can cool neutron stars rapidly by the direct hyperon URCA process. Also, weak reactions with hyperons damp the r-mode instability of rotating neutron stars and their gravitational wave emission. In those latter two cases, hyperon pairing will affect those cooling rates and the viscosity of dense neutron star matter. Finally, hyperons can be produced thermally in supernova matter so that there is a finite amount of strangeness present which can trigger the phase transition to quark matter. A first order QCD phase transition can be read off from the neutrino spectrum by a pronounced second peak in antineutrinos emitted from a galactic supernova.

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