Hyperstars: Phase Transition to (Meta)-Stable Hyperonic Matter in Neutron Stars

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Recent progress in the understanding of the high density phase of neutron stars advances the view that a substantial fraction of the matter consists of hyperons. The possible impacts of a highly attractive interaction between hyperons on the properties of compact stars is investigated. We find that the equation of state exhibits a second stable minimum at large hyperon contents which is in accord with existing hypernuclear data. This second solution gives rise to new effects for neutron star properties which are similar to the ones proposed for the deconfinement transition to strange quark matter and absolutely stable strange stars. We find that the corresponding hyperstars can have rather small radii of $R = 6$–8 km independent of the mass.

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Neutron stars are an excellent observatory to probe our understanding of the theory of strongly interacting matter at extreme densities. The interior of neutron stars is dense enough to allow for the appearance of new particles with the quantum number strangeness besides the conventional nucleons and leptons by virtue of weak equilibrium. There is growing evidence that hyperons appear as the first of the strange hadrons in neutron star matter at around twice normal nuclear density [1], as has been recently confirmed within effective nonrelativistic potential models [2], the Quark-Meson Coupling Model [3], extended Relativistic Mean-Field approaches [4,5], Relativistic Hartree-Fock [6], Brueckner-Hartree-Fock [7,8], and chiral effective Lagrangians [9]. The onset of the hyperon formation is controlled by the attractive hyperon-nucleon interaction which can be extracted from hyperon-nucleon scattering data and hypernuclear data. The hyperon population rapidly increases when continuing towards higher density, eventually even exceeding that of the nucleons. The question arises to what extent does the interaction between the hyperons, which is essentially unknown, influence the overall properties of the compact star.

In this Letter, we will demonstrate that a first order phase transition to strange hadronic matter due to highly attractive hyperon-hyperon interactions can drastically change the global features of neutron stars. Simultaneous mass and radius measurements of a single neutron star can reveal or rule out the existence of such a novel form of matter with exotic properties, which is in accord with our present knowledge of hadronic physics. It is this enormous number of hyperons in neutron stars which enables the formation of such exotic states with strangeness.

Nuclear systems with strangeness, hypernuclei, have been studied in the last decades both experimentally and theoretically. From these studies we know that the nucleon-Λ interaction is attractive and that the Λ feels a potential of about $U_\Lambda = -27$ MeV in bulk matter [10]. The Σ hypernucleus, ${}^4_\Sigma$He, as reported in [11], is bound by virtue of the strong isovector potential of the Σ. On the other hand, extrapolated Σ^- atomic data indicate that the isoscalar potential is repulsive in the nuclear core [12]. An attractive potential for the double strange hyperon Ξ of $U_\Xi = -21$ to -24 MeV has been extracted from the few Ξ hypernuclear events [13]. Recent experiments at KEK [14] and at Brookhaven's AGS [15] confirm the attractive potential for the Ξ from final state interactions albeit a smaller value of -14 MeV is found. The $\Lambda\Lambda$ interaction as deduced from the three double Λ hypernuclear events is highly attractive (see [16] and references therein). It is even stronger than the Λ-nucleon interaction. There is no experimental information about the other hyperon-hyperon interactions, such as e.g. $\Sigma\Xi$ and $\Xi\Xi$.

A recent version of the Nijmegen soft-core potential fitted to nucleon-nucleon and hyperon-nucleon scattering data finds extremely attractive hyperon-hyperon interactions which even allow for the possibility of deeply bound states of two hyperons [17]. Strange hadronic matter in general will consist of nucleons and arbitrary numbers of the hyperons Λ, Σ, Ξ, and Ω^-. If the hyperon-hyperon interaction is only slightly attractive, strange hadronic matter in bulk is bound and purely hyperonic nuclei (MEMO's) are predicted to exist [18]. The driving force is the Pauli-blocking in the hyperon world, which forbids Ξ's to decay to Λ's. Strange hadronic matter is metastable, i.e. it decays on the timescale of the hyperon weak decay of $\tau \approx 10^{-10}$ s by loosing one unit of strangeness. There are two possibilities to circumvent this weak decay and make strange hadronic matter stable on the timescale of the lifetime of the universe.

First, there is a second minimum in the equation of state at a large strangeness fraction besides the normal minimum at zero strangeness. Strange hadronic matter sitting at that local second minimum can not decay by

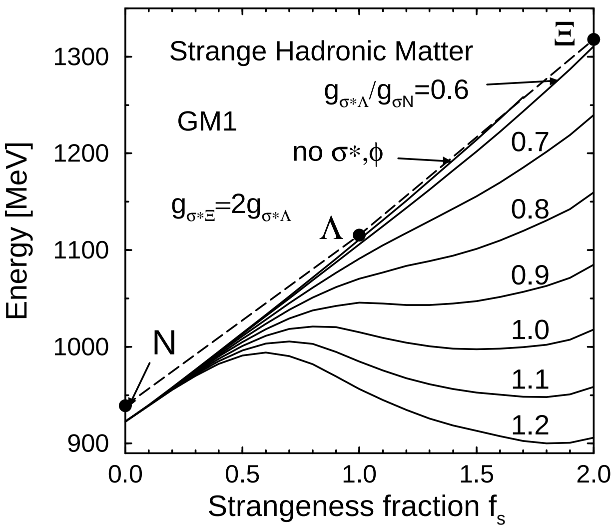

FIG. 1. Equation of state of strange hadronic matter for different strengths of the hyperon-hyperon interactions. A second stable minimum appears at large strangeness fraction f_s which can be deeper than ordinary matter.

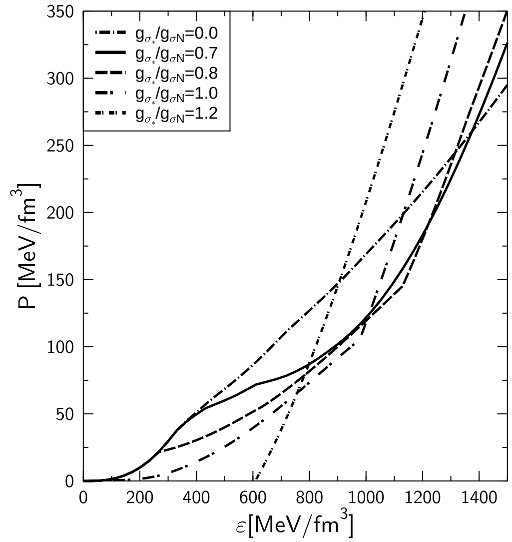

FIG. 2. Equation of state in β equilibrium (neutron star matter) for different strengths of the hyperon-hyperon interactions. A broad mixed phase region (bounded by the two kinks in the curves) is visible for intermediate attraction ($g_{\sigma^*}/g_{\sigma N} = 0.7$–$1.0$). Absolute stable strange hadronic matter ($g_{\sigma^*}/g_{\sigma N} = 1.2$) starts at a finite energy density as in the case for absolutely stable strange quark matter.

a single weak decay as this is energetically forbidden. Such material can only decay by multiple weak decay which is however highly suppressed so that lifetimes will be extremely long.

Secondly, strange hadronic matter is absolutely stable [19]. Once formed, it can not decay to ordinary baryons. Again there must be a energy barrier between this exotic novel form of matter and normal matter (nuclei and hypernuclei) which are known to be stable. Note that hypernuclear data do not exclude the possibility of deeply bound multiply strange systems as it only probes nuclear systems with one or two units of strangeness.

In the following we explore the consequences of these two scenarios for the properties of neutron stars. We take the Relativistic Mean-Field model and the parameterization of Glendenning and Moszkowski [20] for the nucleonic part of the equation of state. The hyperonic coupling constants are fixed to hypernuclear potential depths and by using constraints from SU(6) symmetry, i.e. from the simple quark model. Effects from the hyperon-hyperon interactions are simulated via hidden strange meson exchange of σ^* and f_0 mesons [21]. The coupling constants determining the hyperon-hyperon interaction, i.e. the coupling constants of the hyperons to the σ^* meson ($g_{\sigma^* Y}$ for $Y = \Lambda, \Sigma, \Xi$), can not be fixed by experimental data. They are varied to scan the effects of the depth of binding energy in hyperon matter. We allow these coupling constants to scale with the number of strange quarks of the hyperon. The magnitude of the coupling constant of the Λ hyperon to the σ^* meson is taken close to the corresponding nucleon σ meson coupling constant $g_{\sigma N}$.

Figure 1 shows the total energy per baryon of strange hadronic matter as a function of the strangeness fraction f_S, i.e. the number of strange quarks per baryon. The dashed line between the baryons denotes the border between bound and unbound strange hadronic matter. Even in the absence of the hidden strange meson exchange, strange hadronic matter is bound up to $f_S \approx 1.6$. If the hyperon-hyperon interaction is turned on by increasing $g_{\sigma^*\Lambda}$, the matter is more deeply bound at large f_S. Note that the curves for $f_S \lesssim 0.3$ hardly change and are compatible with hypernuclear data which probe $f_S \leq 1/3$, i.e. for the lightest hypernucleus ${}^3_\Lambda$H. For $g_{\sigma^*\Lambda} \gtrsim 0.9 g_{\sigma N}$ a local second minimum appears at large $f_S > 1$. Matter in this minimum is long-lived as it can only decay into nucleons through a multiple weak decay. The minimum is shifted below the nucleon mass for larger values of $g_{\sigma^* Y}$, thus creating absolutely stable strange hadronic matter. The collapse of nuclei into this absolutely stable form is prohibited, as it would violate strangeness conservation.

Let us discuss now the possible implications of deeply bound strange hadronic matter for compact astrophysical objects. The equation of state (EoS) for charge neutral β-equilibrated neutron star matter is plotted in Fig. 2. A first order phase transition to strange hadronic matter appears which is seen as a pronounced softening of the EoS. The two kinks in the EoS mark the beginning and the end of the mixed phase coexisting of normal and hyperonic matter.

Larger σ^*-hyperon coupling constants yield a lower

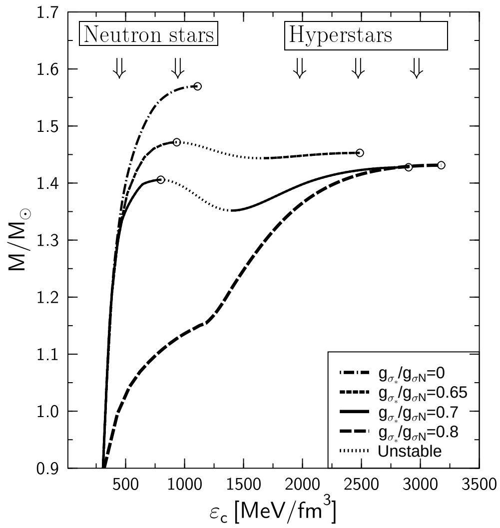

FIG. 3. Neutron star mass versus the central energy density. A second maximum appears due to the highly attractive hyperon-hyperon interaction.

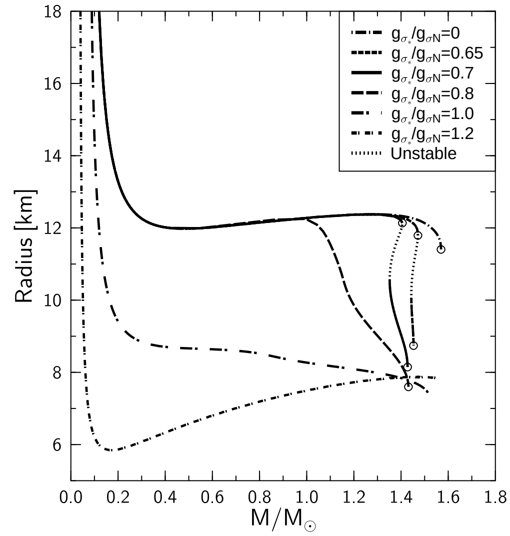

FIG. 4. Mass-radius relation for neutron stars. For the case $0.72 > g_{\sigma^*}/g_{\sigma N} > 0.65$ we see a twin-star behavior, i.e. two neutron stars with identical masses but different radii are possible. Hyperstars are characterized by a rather small radius of about $R = 6$–8 km.

critical energy density for the onset of the mixed phase region and a lower value for the energy density above which a pure state of hypermatter exists. For the case of absolutely stable matter, the EoS exhibits a finite value of the energy density even for vanishing pressure. This is a clear indication for self-bound matter. The compact star consists then solely of hypermatter and can be only surrounded by matter below the neutron drip line density, i.e. by a lattice of nuclei with electrons. Every free neutron will be immediately absorbed at the surface and transformed into a hyperon.

The structure of static spherical symmetric compact objects can be determined by solving the Tolman-Oppenheimer-Volkoff equation [22]. We use the results of Baym, Pethick, and Sutherland [23] to describe the crust consisting of electrons and nuclei below the density $\rho_B < 0.001$ fm^{-3}. For densities of $0.001 < \rho_B < 0.08$ fm^{-3} the results of Negele and Vautherin [24] are employed.

The global feature of the neutron star changes drastically when the hyperon-hyperon interaction is switched on, even for small hyperon coupling constants (see Figs. 3 and 4). Without σ^* meson exchange we find a maximum mass of $M_{\rm max} = 1.57 M_\odot$ with a minimum radius of $R_{\rm min} = 11.4$ km. The maximum density in the center of the star reaches $\rho_c = 0.92$ fm^3 which corresponds to about six times normal nuclear density. Increasing the hyperon-hyperon interactions yields a lower maximum neutron star mass and a second stable solution appears for a range of parameters ($0.72 > g_{\sigma^*}/g_{\sigma N} > 0.65$).

This second solution predicts a undiscovered third family of compact stars. It is located beyond white dwarfs and ordinary neutron stars, with similar masses as predicted for neutron stars but with considerably smaller radii. Such neutron star twins originate from the strong first order phase transition to hypermatter. Compact stars belonging to this third family contain a pure core of deeply bound hypermatter and, hence, can be aptly dubbed a hyperstar. The central baryonic densities of these cores are quite high, between 1.3 fm^3 $< \rho_c <$ 2.2 fm^3. The neutron star twin appears only for masses around the maximum possible neutron star mass. The characteristic radius ranges from 7.5 km $< R <$ 10 km (see Fig. 4). It is thus considerably smaller than for ordinary neutron stars. Therefore, the measurement of two neutron stars with similar masses but distinctly different radii will serve as a unique signal for the existence of neutron star twins. The possibility of neutron star twins and a third family of compact stars has been raised earlier in connection with the phase transition to strange quark matter within the MIT bag model [25,26]. We point out that the properties of neutron star twins as derived in our purely hadronic model are similar to the ones found in these works. This seems to indicate that neutron star twins are a generic feature of a first order phase transition in the interior of neutron stars.

If the hyperon-hyperon interaction is increased further, the two separate solutions disappear. The mixed phase starts at lower density, therefore disabling the first solution. The neutron star mass rises continuously with energy density. For these cases, also lighter stars with $M \approx M_\odot$ and below reveal rather small radii. For deeply bound strange hadronic matter ($g_{\sigma\Lambda} = g_{\sigma N}$) and absolutely stable strange hadronic matter ($g_{\sigma\Lambda} = 1.2 g_{\sigma N}$), we calculate radii of $R \approx 8-10$ km and $R = 6-8$ km, respectively, which is nearly independent of the total mass of the hyperstar. The detection of compact stars with such small radii combined with small masses ($M \approx M_\odot$ or below) would therefore clearly signal the existence of a novel absolutely stable form of matter. Hyperstars can have radii as small as 6 km for compact object with masses as low as $M \approx 0.2 M_\odot$. The core is solely composed of pure hypermatter which is surrounded by a halo of nuclei and electrons. The properties as discussed here are in striking similarity to the ones proposed for strange (quark) stars [27]. Strange stars, on the other hand, are built of absolutely stable strange quark matter and can have much smaller radii than normal neutron stars. If one includes a halo of white dwarf matter around the central strange star a new class of dense white dwarfs has been proposed in [28]. Their mass-radius relation is similar to the one shown here in Fig. 4 for absolutely stable strange hadronic matter.

The hadronic counterparts of strange stars (as derived in the model used here) have extreme nuclear properties. They reach central baryonic densities of up to $\rho_c = 2.4$ fm^3 where effects from the hadronic substructure will get important. Related to that, the phase transition to the quark plasma sets in and will alter the picture at least for the most massive objects under consideration. Then hyperstars may be transformed into strange stars, if they exist. Nevertheless, this applies only to hyperstars with $M \approx 1.4 M_\odot$. Lighter hyperstars have considerable lower central densities where the quark structure of hadrons can be neglected.

The conversion from a neutron star into a hyperstar should be a process containing an interplay of astrophysical observables, namely the spin up effect [29], the emission of gravitational waves [30] and the emission of a γ-ray burst [31], as proposed for the conversion of a neutron star to a strange star. For hyperstar twins, the conversion should be a dynamical process, namely a nonspherical collapse. It might have similar properties as a super- or hypernova collapse. The spin-up effect and the emitted γ-ray burst could be observed with radio- and γ-ray detectors, whereas the emitted gravitational waves might be a relevant source for LIGO, VIRGO and GEO600 [32].

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