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Exotic Matter in Compact Stars

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The study of neutron stars serves as a crucial complement to relativistic heavy-ion physics, in addition to its general importance in astrophysics, in the investigation of strongly interacting matter. Whereas heavy-ion collisions sample high-temperature conditions, macroscopic properties of neutron stars (like masses) are determined by the equation of state at low temperatures and high densities. In recent years the discovery of heavy two-solar-mass neutron stars has triggered extensive discussions and publications on the possibility of exotic matter inside of the stars. In this work, a review of the status of modelling heavy neutron stars that contain hyperons and possibly a quark core will be presented. In this context a number of constraints for exotic particles in the core of stars will be discussed. Finally, the possibility of meson condensation will be considered

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1. Introduction

The investigation of properties of strongly interacting matter at high density and temperature is at the center of many theoretical, experimental and observational efforts in current nuclear physics and heavy-ion research. However, very dense and cold matter cannot be produced in heavy-ion collisions, it only occurs naturally in the core of compact stars. Therefore the study of these stars can provide important, yet indirect information on the properties of extremely dense strongly interacting matter. As the central density of compact stars might reach values of up to 10 times nuclear matter saturation density, it is quite natural to assume that the interior of the stars does not only consist of nucleons and leptons, but might be populated by more exotic particles, including hyperons, baryon resonances, mesonic condensates, as well as quark matter. The amount of such exotic matter might, in part, be constrained by determining their influence on the stellar properties. More details of such a discussion will be presented in the following.

2. Model Approach

In order to investigate the properties of hyperonic and hybrid stars, we first introduce the formulation of the hadronic chiral mean field (CMF) model. It is based on a SU(3) extension of a sigma-omega chiral model in a non-linear realization of chiral symmetry, including all lowest hadronic multiplets [1, 2]. The advantage of such an approach is that it also incorporates dynamic mass generation, which allows for a realistic description of chiral symmetry restoration, while being in very good agreement with a range of nuclear and astrophysics properties [3, 4].

The basic interaction term $\mathscr{L}_{\rm int}$ of the approach is based on a linear interaction between SU(3) meson fields and baryons. Reducing the number of fields to the ones relevant for compact stars, it is given by

$$\mathscr{L}_{\rm int} = -\sum_i \bar{\psi}_i [\gamma_0 (g_{i\omega}\omega + g_{i\phi}\phi + g_{i\rho}\rho) + M_i^*]\psi_i \, , \tag{2.1}$$

where the baryon fields ψ_i interact with the mean fields of the vector mesons: the isoscalar ω, the isovector ρ, and the isoscalar field with hidden strangeness ϕ. The coupling strengths g_{BM} follow from a fitting procedure based on SU(6) symmetry as discussed in [1]. The effective baryon masses M_i^* are, apart from a small explicit term M_{0_i}, generated by the coupling of the baryons to the scalar fields as given by

$$M_i^* = g_{i\sigma}\sigma + g_{i\delta}\delta + g_{i\zeta}\zeta + M_{0_i} \, . \tag{2.2}$$

These expressions include couplings to the isoscalar σ, the isovector δ and the hidden-strangeness field ζ. Implementing a non-linear SU(3) symmetric potential for the scalar fields they attain non-zero vacuum expectation values that generate the baryonic vacuum masses (see Ref. [1] for details). In a further step, in order to describe matter at very high densities and temperatures, quarks are introduced that couple to the fields in the same way as baryons, with their own coupling constants [5]. In addition the approach includes a field Φ that effectively represents the Polyakov loop and the deconfinement transition closely following the quark PNJL models [6, 7]. The contribution of the quarks to the grand canonical potential for a temperature T then reads

$$\Omega_q = -T \sum_{i \in Q} \frac{6}{(2\pi)^3} \int d^3k \ln \left(1 + \Phi \exp \frac{E_i^* - \mu_i^*}{T} \right) \tag{2.3}$$

with a corresponding term for the antiquarks. E_i^* is the effective mass $E_i^* = \sqrt{k^2 + M_i^{*2}}$ and μ_i^* denotes the effective chemical potential of particle i: $\mu_i* = \mu_i - g_{i\omega}\omega + g_{i\phi}\phi + g_{i\rho}\rho$.

3. Results

Restricting exotic particles inside of the star in a purely hadronic star to hyperons and adopting the SU(3) model as described in the last section, one can solve the Tolman-Oppenheimer-Volkov equations [8, 9] as it was in done in [10]. As it is discussed in detail in reference [10], this leads to star masses of about $2.1 M_\odot$, in agreement with current observations of heavy neutron stars [11, 12] (note that the calculation has been published before the mass measurement of the two-solar-mass pulsars). The resulting population of hadrons in star matter is shown in Fig. 1. As seen in the figure, hyperons start to populate the star at about 3 times nuclear matter saturation density, the Λ appearing first, followed by the Σ^-. In this particular model calculation, the Ξ^- only appears at densities that are not reached in stable compact stars. The main reason for this is that the strange scalar field, representing the QCD scalar condensate of strange quark-anti-quark pairs, drops slowly with density, keeping particularly states with large strangeness at a high effective mass. Furthermore, the figure shows a rather limited amount of strangeness in stellar matter, which does not exceed a strangeness value of 0.1 per baryon in the center of the most massive star. Apart from the slow drop of the strange condensate, the repulsive force between hyperons mediated by the ϕ meson suppresses the number of hyperons in matter, as it was discussed in detail in Ref. [10]. As a consequence, the hyperons do not change the equation of state significantly, thus still allowing for massive two-solar mass hyper stars.

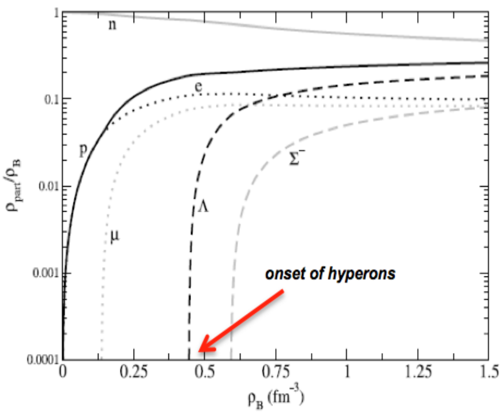

Figure 1: Normalized baryon and lepton densities of beta-equilibrated stellar matter as function of density.

In addition to the nucleonic and hyperonic states from the lowest baryon octet, potentially particles from the spin 3/2 baryon decuplet could occur in stars. This has been studied within the same model approach by including the decuplet [13, 14, 15]. Specifically the Δ baryon states are populated at reasonably low baryon densities because of their relatively low mass, large isospin and, in the case of the Δ^-, its negative charge. Using simple SU(6) relations between the coupling strengths of the octet and decuplet states, the particle population in the star might change quite significantly, while still keeping a reasonable maximum star mass of about 1.9 solar masses [14]. As can be seen in Fig. 3, the Δ baryons replace the hyperons and push their appearance to higher densities. For small deviations from the SU(6) values, which might be favored by various experiments (see discussion in Refs. [16, 15]), many more Δ's could occur in the star, leading to small stellar masses [16]. Thus, this point still requires additional studies and clarification.

There has been long-standing speculation that meson condensates might occur in neutron stars.

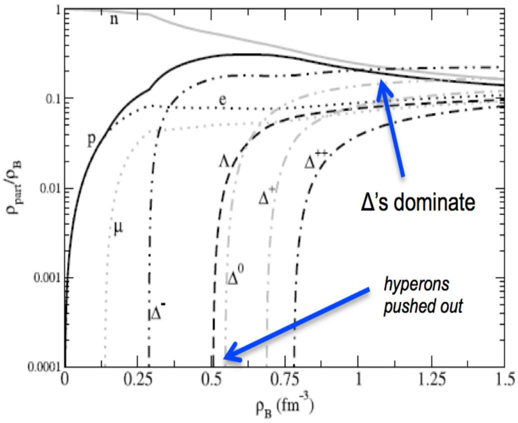

Figure 2: Same as Fig. 1, including Δ baryons in addition to hyperons.

The most likely candidates for such condensation are kans and pions. In particular, the K^- has been studied extensively starting with the pioneering work in [17]. This can be understood intuitively by considering the quark content of the particle. As the K^- consists of anti-up and strange quarks, one would expect rather strong attraction in dense matter. The usual vector repulsion between particles in this case changes to an attractive force between the anti-up quark and all the up and down quarks from the dense medium. On the other hand, the s-quark is supposed not to interact too strongly with the non-strange quarks in the star. However, the non-linearities of the hadronic model yield a suppression of this effect as has been discussed in Refs. [18, 19]. The resulting energy of a K^- at rest in the stellar medium is shown in Fig. 3. When the energy falls below the electron chemical potential, condensation sets in and the K^-'s start to replace the electrons in order to create a charge-neutral system. The left panel shows the result for kaon energies only taking into account a medium of nucleons, whereas in the right panel hyperons are included as well. In the nucleonic case, condensation sets in at about 5.5 ρ_0. This is just about $0.5\rho_0$ below the maximum central density that can be reached in the core of the heaviest star. Thus, the effect of the condensation would be largely negligible. Including hyperons the onset is shifted to even higher values of density that cannot be reached in the star. The reason for the shift is that the appearance of the negatively charged Σ^- reduces the electron chemical potential, which in consequence leads to a higher critical density for condensation.

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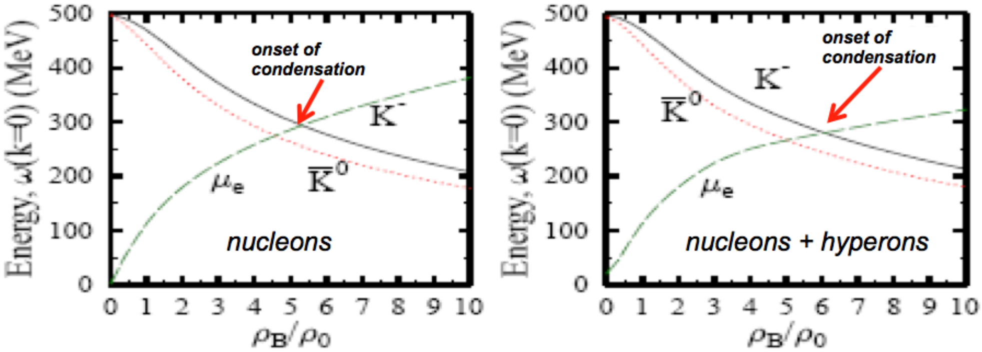

Figure 3: Energy of zero-momentum K^- and $\bar{K}^0$ mesons as function of baryon density. The electron chemical potential is also shown. In the case of the K^-, the crossing of the lines signals the onset of kaon condensation. The left panel shows results for kaons in nucleonic star matter, whereas the right panel also takes into account hyperons.

Another potential mechanism for meson condensation has been discussed in Refs. [20, 21]. In this reference, we investigated condensation of the ρ^- meson. Although the meson mass (of about 776 MeV) is rather large, non-linear interactions, specifically an interaction term between the scalar σ and the ρ meson of the type $\mathscr{L} = g\sigma^2\rho^2$ can effectively lead to a reduction of the ρ mass in the medium due to the drop of the σ field value at high densities. Such interactions can occur quite naturally in SU(3) coupling schemes of vector meson self-interactions (see Refs. [22, 10, 4]). This alone might not be enough to generate ρ condensates in the dense medium for reasonable values of the coupling g. However, this situation changes in strongly magnetized neutron stars. As the ρ meson is a spin 1 particle, it couples strongly to the magnetic field, leading to an effective energy of the lowest level of the meson of

$$(E^*)_\rho = \sqrt{(m^*)^2_\rho - eB} \quad , \tag{3.1}$$

where the effective ρ meson mass is given by

$$m^*_\rho = m_\rho - g\sigma \tag{3.2}$$

In order to determine whether the condensation is realistic, we assume a very strong magnetic field $B = 7 \times 10^{18}$G in the center of the star. This value is at the upper end of what realistically might be possible in a stable star configuration. In addition, in order to keep the calculation simple we adopt a standard relativistic mean field parametrization GM3 [23], modified by Eq. 3.2. In Fig. 4 the numerical results of this study are presented. Depending on the value of the coupling g condensation might set in at densities of about $5\rho_0$. The general effect of the magnetic field does not depend on the magnetic field strength, however, the exact value for the onset of condensation depends on the specific hadronic model. Thus, in general, it is possible that vector meson condensation takes place in magnetized heavy neutron stars.

In addition to a change of the cooling behaviour of the star, this will lead to a softening of the equation of state and, therefore, to a reduction of the maximum star masses. More detailed studies

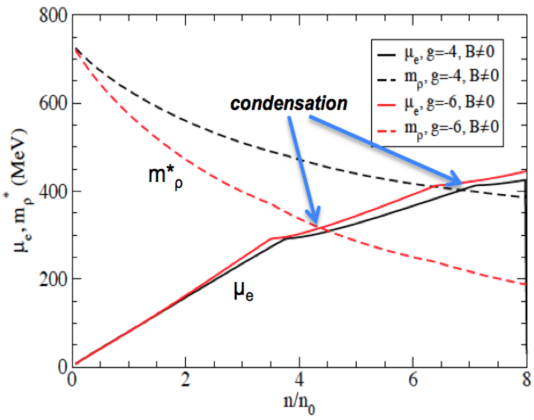

Figure 4: Effective ρ meson mass as function of density in a strongly magnetized neutron star for different coupling strenghts (see text). The solid lines show the corresponding electron chemical potential.

of these effects should be performed in the future. Note, however, that this does not imply a conflict with the observed heavy stars, as the reduction of the stellar masses due to the condensation only takes place for strongly magnetized stars, when the magnetic field itself leads to an increase of the allowed star masses [24].

Recently, there has been discussion involving the systematics of calculations of neutron star radii of typical 1.4 solar mass stars. As it was correctly pointed out in Ref. [25], most models that contain hyperons and that are able to stabilize heavy neutron stars tend to be rather stiff at lower densities, such that the occurrence of hyperons won't reduce maximum star masses to values that are below the two solar mass value. Such models would then disagree with low-density first-principle nuclear matter calculations based on chiral perturbation theory. However, the radius of the star can be strongly affected by a coupling of the isoscalar and isovector vector mesons, e.g. of the form $\mathscr{L}_{iso} = \alpha\omega^2\rho^2$ with a coupling strength α. The influence of such terms have been discussed some time ago in [22, 26, 4]. Adding this term to the purely nucleonic NL3 relativistic mean field model as it was done in [26], as well as to the baryon octet CMF model outlined above, one obtains a modified stellar mass-radius diagram as shown in Fig. 5. Note that in order not to modify the asymmetry energy, the additional term requires a readjustment of the nucleon-ρ meson coupling strength $g_{N\rho}$ as it appearing in Eq. (2.1). The figure shows a significant shift of the stellar radii of typical-mass neutron stars to smaller values, whether the model includes hyperons or not. The shifted solution is in agreement with the constraints for the equation of state analyzed in [25] and still allows for heavy two-solar-mass stars.

Finally, when we include quark degrees of freedom in the model as described in section 2, one can perform a realistic calculation of the equation of state over a large range of temperatures and densities that are relevant for neutron-star physics as well as for the physics of relativistic heavy-ion collisions. The result of such a calculation [27] is shown in Fig. 6. This calculation has been done for isospin symmetric matter with vanishing total strangeness as is appropriate for a fireball created in a heavy-ion collision. As can be seen in the plot, with the exception of the liquid-gas transition around nuclear matter saturation density, there is no first-order transition at any chemical potential or density. In consequence, within this model framework there is also no critical end-point, which is

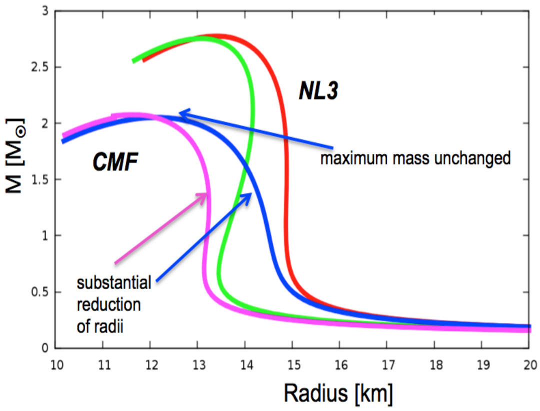

Figure 5: Mass-radius diagram of neutron stars for the NL3 and CMF models. The curves exhibiting smaller radii are obtained by including a strong non-linear coupling between the ω and ρ meson.

one of the central topics of investigation in the heavy-ion research program. The situation changes

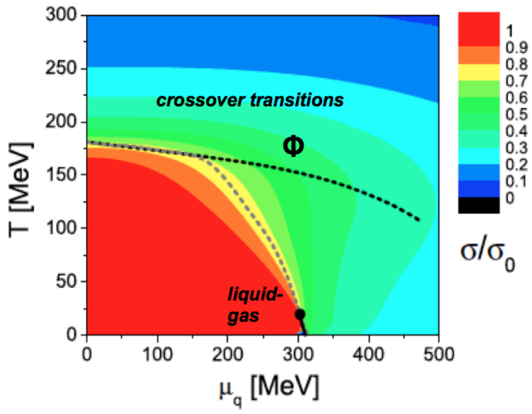

Figure 6: Color-coded representation of the scalar condensate as function of quark chemical potential. The full line represents the first-order liquid-gas phase transition, which continues on as cross-over at higher temperatures. The upper dashed line indicates the maximum of change of the Polyakov loop field Φ.

in beta-equilibrated stellar matter. As was shown in [28], depending on the strength of the vector interaction of the strange quark, a first-order phase transition can occur. Calculating the mass-radius diagram of compact stars for the corresponding equation of state, this effect can be seen as a sudden cut-off of stable stellar solutions. For specific choices of the relative coupling of strange quarks and non-strange quarks to the respective vector fields $\xi = g_{s\phi}/g_{q\omega}$ twin solutions of strangeness-enriched hybrid stars occur with masses around 1.7 solar masses and radii between 9 and 10 km with non-strange counterparts with large masses and larger radii. Thus, within this model there is the possibility of a class of stars with very distinct radii and a changed composition that might lead to observable effects, for instance in their cooling behaviour [28].

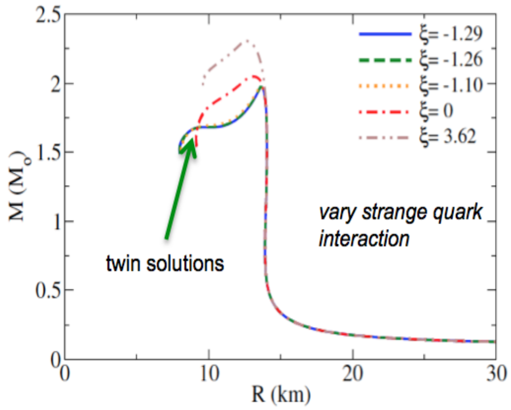

Figure 7: Mass-radius diagram for CMF hybrid star solutions. Results for different relative strengths of the strange and non-strange quark vector repulsion ξ are shown. In one case a second small region of stable hybrid twin stars can be observed.

4. Concluding Remarks

We studied the occurrence of exotic particles in compact stars within a chiral and Walecka-type relativistic mean field approach. Taking into account all interaction channels of the baryon octet, the hyperon content of heavy stars is suppressed and, therefore, does not affect maximum star masses significantly. In addition to the octet states, Δ baryons are quite likely to appear in the star. Depending on the somewhat restricted coupling strengths of the Δ-meson interactions, this could reduce star masses, either only slightly or significantly. The latter scenario would lead to a contradiction with observation and further studies are needed to clarify this point. Within the CMF model, kaon condensation only appears at very high densities and will not affect stellar properties. On the other hand there is a possibility of ρ meson condensation in strongly magnetized high-mass stars.

Including also quarks in the model, depending on the coupling strength of the strange quarks a first-order phase transition to a strangeness-enriched phase might occur in the core of the star. This could lead to the appearance of very compact hybrid twin stars, which might have interesting observable implications.

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