STRANGENESS IN THE CORES OF NEUTRON STARS*

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The measurement of the mass $1.97 \pm 0.04\ M_\odot$ for PSR J1614-2230 provides a new constraint on the equation of state and composition of matter at high densities. In this contribution, we investigate the possibility that the dense cores of neutron stars could contain strange quarks either in a confined state (hyperonic matter) or in a deconfined one (strange quark matter) while fulfilling a set of constraints including the new maximum mass constraint. We account for the possible appearance of hyperons within an extended version of the density-dependent relativistic mean-field model, including the ϕ meson interaction channel. Deconfined quark matter is described by the color superconducting three-flavor NJL model.

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1. Introduction

The measurement of the mass $1.97 \pm 0.04 M_\odot$ for PSR J1614-2230 by Demorest *et al.* [1] has renewed the interest in the question of the internal structure of a neutron star (NS). This concerns, in particular, the question of its composition and the possibility of exotic forms of matter in the cores of NSs which has been tested extensively against this new measurement [2,3,4,5], thus reviving an old controversy [6,7] in the course of which it had been shown that hybrid stars with quark matter cores could not be ruled out by the observation of a $2M_\odot$ compact star [8].

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This was demonstrated not only within extended bag models [2, 4] but also within the field theoretical Nambu–Jona-Lasinio (NJL) model description of quark matter [8, 9]. In the latter approach, it was found that the hybrid star becomes unstable as soon as strange quark matter (in its color superconducting CFL phase) appears in the very core of the hybrid star. If one combines the NJL-model description of color superconducting quark matter with an additional (possibly density dependent) bag pressure, then it is possible to achieve stability of hybrid stars even with strange quark matter interior [10], eventually fulfilling the $2M_\odot$ constraint from PSR J1614-2230 [5, 11, 12]. There appears a new question which we would discuss here: Given a high-mass hybrid star contains quark matter, could this be strange quark matter?

A separate issue is the possible appearance of hyperons at supersaturation densities, before a phase transition to quark matter occurs. It was found that the appearance of hyperons softens the equation of state (EoS) to the extent that sufficiently massive hybrid stars cannot be described. In the Brueckner–Bethe–Goldstone (BBG) theory even the typical NS mass of $\sim 1.4\ M_\odot$, well measured for binary radiopulsars, could not be reached [13]. An early deconfinement transition to bag model quark matter with a density-dependent bag constant was suggested as a possible solution [14]. Within the density-dependent relativistic mean field (RMF) theory of neutron star matter [15] higher maximum masses than in BBG theory could be reached and the inclusion of repulsive ϕ meson interactions provided a stiff enough EoS to support a $2M_\odot$ star with hyperonic interior [5, 16].

In the present contribution, we discuss hybrid stars with both, hyperonic and quark matter interior in the light of the new maximum mass constraint.

2. Model setup and results

The hadronic equation of state is described by a RMF using the parametrization DD2 [17] that was fitted to properties of finite nuclei. The model was extended to include all hyperons of the baryon octet in a similar spirit as in Ref. [15]. The couplings of the hyperons to the ω and ρ mesons are obtained from a SU(3) rescaling of the nucleon–meson couplings with an additional overall factor $R = 0.83$ that is close to the one given in [15]. The coupling of the σ meson to the hyperons was determined such that the hyperon potential in symmetric nuclear matter at saturation assumes the values $U_\Lambda = U_\Sigma = -30$ MeV and $U_\Xi = -21$ MeV, respectively. A repulsive interaction between the hyperons was modeled by the exchange of the $\phi(1020)$ vector meson with a coupling constant given by the ω-nucleon coupling at saturation density with a SU(3) scaling and the same reduction factor R as for the nucleon–meson couplings.

Quark matter is described by the color superconducting three-flavor NJL model with scalar, diquark and vector interaction [18]. Parameters of the model are chosen from Ref. [19][1] for the NJL model case with a constituent quark mass of $M(p=0) = 367.5$ MeV.

We add a correction to the quark pressure to account for the melting of the gluon condensate due to the influence of dynamical quarks which appear in the system for $\mu > \mu_c$, *i.e.* above the critical chemical potential $\mu_c = 1047$ MeV for chiral symmetry restoration. The pressure of the quark matter subsystem is then $p_{\rm quark}(\mu) = p_{\rm NJL}(\mu) - B(\mu)$, where the additional contribution is understood as a chemical potential dependent bag pressure

$$B(\mu) = B_0 \left[\exp\left(-\frac{\mu - \mu_c}{\delta\mu} \right) - 1 \right] , \qquad \mu > \mu_c \, , \tag{1}$$

and $B(\mu) = 0$ elsewhere. The resulting correction to the density is

$$\Delta n(\mu) = -\frac{\partial B(\mu)}{\partial \mu} = \frac{B_0 + B(\mu)}{\delta\mu} \, , \tag{2}$$

which entails a contribution to the energy density

$$\Delta\varepsilon(\mu) = \varepsilon_{\rm quark}(\mu) - \varepsilon_{\rm NJL}(\mu) = B(\mu) + \mu \Delta n(\mu) \, . \tag{3}$$

We report results for the parameters $B_0 = 40$ MeV/fm^3, $\delta\mu = 100$ MeV.

The hadronic-to-quark-matter phase transition is described by a Maxwell construction whereby the neutron star constraints are fulfilled locally, *i.e.*, separately for the EoS of the two phases. The resulting hybrid EoS is then used for solving the Tolman–Oppenheimer–Volkoff equations. In Fig. 1, we present the sequences of two hybrid star configurations obtained for two sets of NJL model parameters and a purely hadronic EoS for comparison. We observe that for both hybrid star sequences the maximum mass is higher than that for the purely hadronic case. This result needs an explanation. After the first crossing of $p_{\rm hadron}(\mu)$ and $p_{\rm quark}(\mu)$, which defines the deconfinement phase transition, there is a second crossing of both pressure curves due to the softness of hyperonic matter which is reflected in a steeper rise of $p_{\rm hadron}(\mu)$ than of $p_{\rm quark}(\mu)$ at high densities. We disregard the second crossing by the argument that once hadrons are dissolved by compressing hadronic matter and thus deconfinement occurred, a further compression cannot restore the hadronic phase. The hyperonic degrees of freedom become irrelevant and their EoS can be ignored beyond the first transition point. For a discussion of multiple crossing of pressure curves and the so-called masquerade problem, see [20].

[1] This parametrization scheme has been implemented in an online tool developed by F. Sandin which also corrects for a mistake in the kaon mass formula employed in [19], see `http://3fcs.pendicular.net/psolver`

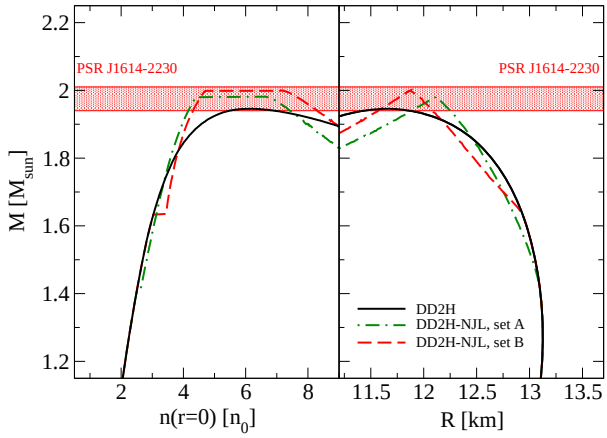

Fig. 1. Mass *versus* central density (left panel) and *versus* radius (right panel) for pure DD2 with hyperons (solid lines) and for two hybrid EoS with $\eta_V = 0.4$: set A with $\eta_D = 1.0$ (dash-dotted lines) and set B with $\eta_D = 0.9$ (dashed lines).

In Fig. 2, we present the internal structure of the configurations with mass $M = 1.94\ M_\odot$, which is the maximum mass obtained in the purely hadronic case. We note that due to the softness of the hadronic EoS with hyperons the central density in the maximum mass hyperonic star exceeds 6 n_0, where n_0 is saturation density. This configuration has an extended hyperonic inner core and a relatively thin ($\sim$ 2 km) purely nucleonic outer

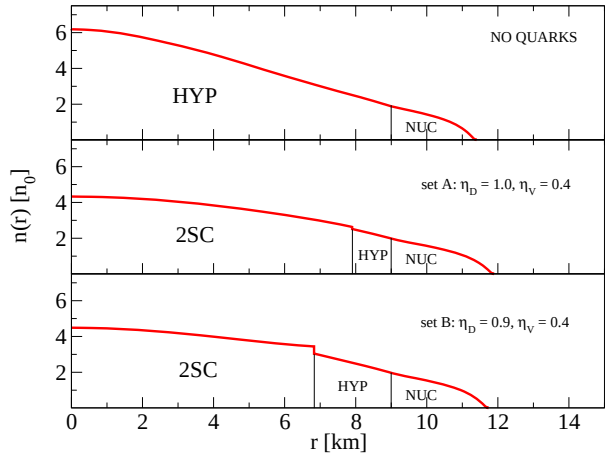

Fig. 2. Structure of compact stars for a mass 1.94 $M_\odot$ within the limits provided by PSR J1614-2230, for three cases: without quark matter (upper panel), with quark matter for set A (middle panel), and with quark matter for set B (lower panel).

core. The two hybrid configurations with a deconfinement transition have a two-flavor color superconducting (2SC phase) quark matter core extending up to 2/3 of the star's radius. Their inner core is surrounded by layers of hyperonic and purely nucleonic matter, respectively.

We should note a certain peculiarity of the model. Hyperons contain strangeness while the quark matter in the core is in the 2SC phase. Hence we have a situation, where strangeness is confined to a layer of hyperonic matter at moderate densities, while the deconfinement phase transition at higher density liberates sequentially first the light flavors and only at still higher densities also the strange quarks [21]. Once this occurs, the matter softens and the star collapses so that the mass at which this critical density is reached in the center is the maximum mass for hybrid stars.

3. Conclusion

We conclude that one can obtain hyperon stars fulfilling the new $2M_\odot$ mass constraint. This requires the repulsive ϕ meson interaction channel. Straightforward attempts to construct three-phase hybrid stars fail to meet the new mass constraint. With a phenomenological μ-dependent contribution to the quark pressure motivated by backreaction from the gluon sector a deconfinement phase transition could be obtained with hybrid star sequences fulfilling the new maximum mass constraint. It is plain that traditional phase transition constructions introduce inconsistencies like a "second crossing" of pressure curves and should be replaced by a microscopic description of hadron dissociation at high densities, to be developed.

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