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Modeling Hybrid Stars and Hot Matter

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Abstract

The core of neutron stars consists of extremely dense matter at relatively low temperatures. In such an environment the appearance of exotic strongly interacting particles beyond nucleons appears quite natural. In this context we consider hybrid stars that, in addition to nucleons and hyperons, also contain quarks as further degrees of freedom. We investigate the impact of quarks on the properties of these compact stars. In addition, we discuss new constraints on such objects arising from the recently measured gravitational wave signal of two merging neutron stars.

Keywords: neutron star, hybrid star, phase transition, hyperons

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1. Introduction

There are two major approaches to a deeper understanding of strongly interacting matter at high densities and/or temperatures. Relativistic heavy-ion collisions create a hot fireball with relatively low net baryon density at high beam energies reached at RHIC or LHC. Studying such systems at higher densities but still high temperatures (on an astrophysical scale) is the goal of the RHIC beam energy scan, as well as a central research topic for the upcoming facilities FAIR at GSI and NICA in Dubna. On the other hand, compact star physics traditionally covers the physics of rather cold but very dense matter, although the core of a proto-neutron star potentially reaches temperatures of 30 MeV or higher [1]. With the first observation of a neutron star merger in 2017 [2], astrophysical environments can be studied where temperatures beyond 80 MeV might occur in the intermittent hypermassive neutron star. Thus, one obtains an overlap of heavy-ion and compact star physical conditions, albeit for different isospins. This new situation underlines the need for theoretical approaches that cover all the range of densities and temperatures from nuclei to the quark-gluon plasma in a consistent unified way.

2. Modeling Quark-Hadron Matter

In order to be able to describe hadron and quark matter as well as the transition between the two asymptotic phases, it is in general not sufficient to define a hadronic model and quark model and glue them together. As one problem of such an approach, the transition will be first-order throughout (except perhaps at one

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point), which is in contradiction to the lattice QCD findings of a cross-over transition at high temperatures and zero baryon chemical potential [3, 4]. In our approach this problem is solved in a practical manner by using the well-established relativistic CMF (chiral mean field) model for hadronic matter that includes the lowest hadronic SU(3) multiplets [5, 6, 7]. The interaction is generated by linear couplings of the baryons with the mesonic mean fields:

$$\mathcal{L}_{\text{int}} \quad = \quad -\sum_i \bar{B}_i[\gamma_0(g_{i\omega}\omega + g_{i\rho}\rho) + g_{i\phi}\phi + m_i^*]B_i \; . \tag{1}$$

where the ω and ρ fields are the 0th components of the non-strange isoscalar and isovector vector fields and the ϕ is the field with hidden strangeness. Apart from a small explicit term m_{0_i} the effective baryon masses m_i^* are generated by the coupling of the baryons to the scalar fields as given by

$$m_i^* \quad = \quad g_{i\sigma}\sigma + g_{i\delta}\delta + g_{i\zeta}\zeta + m_{0_i} \; . \tag{2}$$

Here, the σ, δ, and ζ are the scalar fields analogous to the ω, ρ, and ϕ. Meson self-interaction terms generate non-vanishing vacuum expectation values for the scalar fields and , via the coupling to the baryons, baryonic masses.

In order to describe hybrid stars, quarks are included as additional degrees of freedom that couple to the mean fields as well. Following the formulation of quark PNJL models [8, 9], an effective field is introduced that couples to the quarks and corresponds to a deconfinement order parameter. It has the effect of suppressing quarks at low densities and/or temperatures, which then appear in the strongly excited system [10, 11]. The hadrons are suppressed in the quark phase by introducing a thermodynamically consistent excluded volume, as discussed in detail in Ref. [10]. Note that this does not lead to a superluminous speed of sound, e.g. at high density, as is usually the case for hadronic models with excluded volume, since the system changes to a quark-dominated phase, where there is no excluded volume correction.

3. Hybrid Stars

Stellar properties can be calculated in the model as described above by computing the equation of state for charge-neutral beta-equilibrated matter and integrating the Tolman-Oppenheimer-Volkov equations for static spherically symmetric stars [12, 13]. Depending on the vector-meson coupling strength of the quarks, different results for the stellar mass-radius diagram can be obtained. For a particular choice of parameters, for details see Ref. [14], a twin star solution at around 1.6 solar masses appears with a significantly different radius as the corresponding star on the main branch differing by about 5 km as indicated in Fig. 1.

One general problem with such a calculation, and many related calculations in the literature, is that strong repulsive interactions between quarks lead to very big deviations in the Taylor coefficients of the expansion of the pressure in terms of the baryochemical potential, which can be quite accurately determined in lattice QCD simulations. This is routinely used to stiffen the quark equation of state and generating high-mass neutron stars. A detailed discussion of this point can be found in Refs. [15, 16].

In extended studies within the same approach of combining hadronic and quark degrees of freedom as discussed above, we adopt the parity-doublet model for the baryons, where baryons are described as doublets together with their corresponding negative parity states. In an SU(2) version of such an approach, the effective energies of the nucleons read

$$m_N^*(\pm) = \sqrt{(g_{\sigma N}\sigma)^2 + m_0^2} \mp g'_{\sigma N}\sigma \;\; , \tag{3}$$

where m_0 is a chirally invariant mass term [17] and ± refers to the two parity states. There are two possible couplings g, g' to the scalar σ field. As one can see from this expression, when the field vanishes, both states are degenerate in mass. In an SU(3) version of this approach [18, 19, 20], the quark vector interaction is set to zero to avoid the aforementioned conflicts with lattice QCD data. Fig. 2 shows a comparison of first

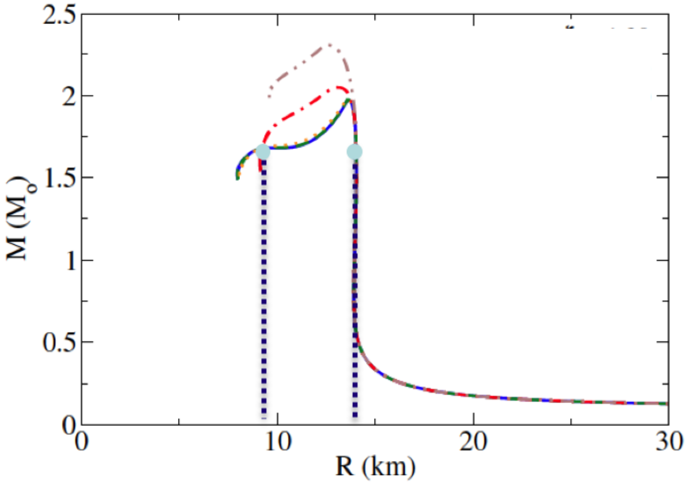

Fig. 1. Mass-radius diagram for the hadron-quark CMFq model with strong vector quark-quark interactions. At smaller radii, twin star solutions develop with distinctive different radii.

lattice and model results for the temperature dependence of the masses of the Λ and its parity partner. There is at least qualitative agreement. In both cases, the parity partners become degenerate around T_c, where the parity partner of the Λ drops steeply in mass, whereas the usual Λ mass changes only weakly.

The maximum mass in the corresponding model that can be achieved is 1.98 solar masses, in good agreement with observation [21, 22]. Note that in this case essentially all compact stars contain a phase with baryons and quarks, where the baryons have vector repulsion and keep the equation of state stiff enough for generating heavy neutron stars. As this model can be applied to the whole range of densities and temperatures, hydrodynamical simulations of heavy-ion collisions as well as neutron star merger simulations are currently being investigated.

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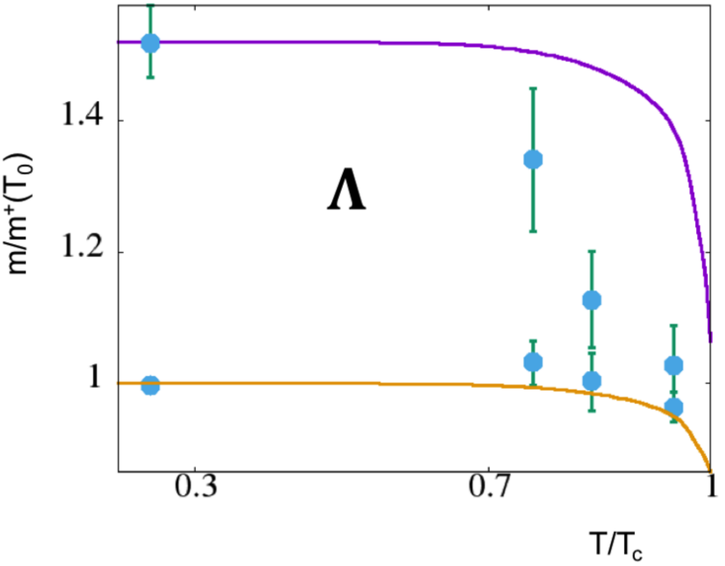

Fig. 2. Mass of the Λ baryon and its parity partner as function of scaled temperature T/T_c for vanishing chemical potential. The lines denote the model results whereas the symbols mark lattice QCD data (from Ref. [23]).

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